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THE KENTLAND AREA OF DISTURBED ORDOVICIAN ROCKS IN NORTHWESTERN INDIANA

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ABSTRACT

In the southern part of Newton County, in the northwestern part of Indiana, strata of Middle Ordovician (St. Peter, Black River, Galena) age are exposed at the surface, surrounded on all sides, so far as is known, at lower elevations by younger strata. The exposed beds have been uplifted vertically about 1,500 feet and now exhibit very high dips, in some cases being vertical or even overturned. The disturbed area, so far as its limits are at present known, covers less than one square mile and exhibits both folding and faulting; the latter phenomenon being the common way in which the rock failed under stress. A Middle Ordovician sequence of about 400 feet of dolomites, limestones, sandstones, and shales, containing a fauna of over seventy-five species, is involved in the deformation and exhibited at the surface. The present structural conditions appear to have resulted from "cryptovolcanic" activity.

INTRODUCTION

The only area known in Indiana which exhibits intense crustal deformation is found about 3 miles east of Kentland, southern Newton County, in the northwestern part of the state (see Fig. 1). Here in a small circumscribed area the strata literally stand on end and exhibit much fracturing and faulting with a minor amount of folding. The rocks involved in the deformation are normally at least 1,500 feet below the surface in the immediate vicinity.

Just fifty years ago Collett[1] first pointed out that rocks of Ordovician age outcrop east of Kentland, but strangely enough little detailed work has been attempted to determine either the stratigraphic position and sequence of the beds or the structural conditions which bring rocks of such an age to the surface amidst strata of Devonian, Mississippian, and perhaps Pennsylvanian age.

During the past five years the authors have visited on a number of occasions the three quarries east of Kentland. Detailed maps have been made, stratigraphic sections have been measured, and a considerable collection of fossils has been made.[2]

It is the purpose of this paper to present such facts as are now at hand with the hope that as additional data accumulate in the future a fuller understanding and explanation of this puzzling structure may result.

LOCATION

The area here described is located in the north one-half of Sec. 25, T. 27 N., R. 9 W., along the south line of Newton County, 3 miles east of Kentland. Exposures are limited to three quarries all of which lie in the northern half of the section. United States Highway No. 24 passes along the northern side of the area (see Fig. 1).

Rock exposures are rare in the flat glacial plain of the Kentland

[1] J. Collett, "Geological Survey of Newton County," *Ind. Dept. Geol. and Nat. Hist., 12th Ann. Rept.* (1883), pp. 58–59.

[2] The writers take this opportunity for expressing their appreciation of the willing and helpful assistance given by numerous students and geologists during this study. R. Bates and J. W. Huddle, Indiana University, and W. L. Wilgus, University of Wisconsin, aided in making the large detailed structural map of the McCray Quarry. E. A. Mayer and G. O. Raasch, University of Wisconsin, collected many of the fossils listed below, and the latter together with H. L. Lloyd assisted greatly in the identification of many of the species. Dr. Justin Zinn, University of Wisconsin, made the magnetic survey upon which the magnetic map Figure 7, is based. Further acknowledgments will be made in the proper place.

Dr. R. T. Chamberlin has from the beginning of the study manifested a keen interest in it and has offered numerous valuable suggestions. He led a group of geologists and students from the University of Chicago on a trip to Kentland on Saturday, November 21, 1931, and acknowledgments are hereby made to that enthusiastic group for any suggestions or material they furnished.

Finally, the authors are grateful to Professors Stark and Lamey, Northwestern University, and their group of very helpful students, who spent three days (November 20–22, 1931) with the authors studying and collecting in the Kentland quarries. It was this group that found the fossils in the sandstone and kindly sent them on to the authors.

vicinity. At the quarry locality the glacial drift is thin and natural exposures were present before the quarries were opened. Short distances away, however, in all directions rock lies fifty or more feet below the flat surface of the glacial plain. Slightly higher ground marks the quarry sites.

REVIEW OF PAST WORK

Until the reef character of the so-called "domes" along the upper Wabash River (middle northern Indiana) was demonstrated, the

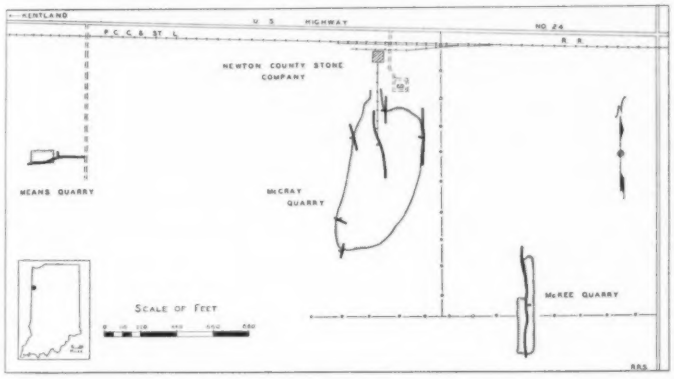


FIG. 1.—Map showing the location of and structural conditions in the quarry district 3 miles east of Kentland, Indiana.

structural puzzle at Kentland was generally considered to have had the same origin as the "domes." Regardless, however, of what their interpretation of the "domes" was, nearly every observer realized that the deformed condition of the rocks near Kentland must have resulted from diastrophic movements. The misinterpretation of the "domes" and the failure of many geologists to accept G. K. Greene's early reference of the rocks to the Ordovician have been largely responsible for the little attention that has been paid to one of the most interesting and puzzling geological problems in Indiana.

Collett[3] long ago called attention to the disturbed condition of the rocks in the exposures east of Kentland. He attributed the unusual attitude of the strata to either "dislocations" or "false bedding," and

[3] *Op. cit.*, pp. 58–59.

referred the beds to the Ordovician on the basis of fossils collected by Mr. G. K. Greene.

Gorby[4] considered the tilted condition of the Silurian rocks in northern Indiana to indicate a great anticlinal, the "Wabash Arch," which he thought to extend "entirely across the State." He erroneously called the rocks at Kentland "Niagaran," and also confused the structure there with that of the reefs of the upper Wabash Valley. From his data Gorby concluded, "The inference, then, is that the disturbances occurred at the close of the Upper Silurian formation, and before the beginning of the deposition of the Devonian rocks." He considered the thin brachiopod shells found in one of the quarries to "have evidently been carried up through crevices in the rocks by the force of escaping steam or gas from below."

Because of the misunderstanding of both the age of the strata at Kentland and their relations to the "domes" (reefs) along the upper Wabash Valley, Gorby, and Thompson[5] after him, advanced a theory —that of the "Wabash Arch," which is untenable with present knowledge as has been pointed out.[6]

Ashley[7] in discussing the coal deposits of Indiana briefly referred to the structural conditions east of Kentland and concluded that, "From the radiating direction of the dips it would almost seem as though volcanic or other agencies had produced an upheaval of a kind seldom found in nature."

Kindle[8] recognized the condition of the beds at Kentland as due to deformation. His confusion of the age of the rocks involved, however, makes his statements concerning the strata along the

[4] S. S. Gorby, "The Wabash Arch," *ibid.*, *15th Ann. Rept.* (1886), pp. 228–41.

[5] M. Thompson, "The Wabash Arch," *ibid.*, *16th Ann. Rept.* (1889), pp. 41–53; "Geological and Natural History Report of Carroll County," *Ind. Dept. Geol. and Nat. Res.*, *17th Ann. Rept.* (1892), pp. 171–91 (182–85).

[6] E. R. Cumings and R. R. Shrock, "The Geology of the Silurian Rocks of Northern Indiana," *Ind. Dept. Conserv. Pub. No. 75* (1928), pp. 14–16 *et. seq.*

[7] G. H. Ashley, "The Coal Deposits of Indiana," *Ind. Dept. Geol. and Nat. Res.*, *23d Ann. Rept.* (1899), pp. 184–91.

[8] E. M. Kindle, "The Niagara Domes of Northern Indiana," *Amer. Jour. Sci.* (4), Vol. XVI (1903), pp. 459–68. See also "The Stratigraphy and Paleontology of the Niagara of Northern Indiana," *Ind. Dept. Geol. and Nat. Res.*, *28th Ann. Rept.* (1904), pp. 397–428; E. M. Kindle and C. L. Breger, "Paleontology of the Niagara of Northern Indiana," *ibid.*, pp. 428–86, plates.

Wabash River untenable for the Kentland area. Of special interest is Kindle's statement that, "Rocks of later age have been encountered at much lower levels in all directions from this point within two or three miles, and it appears probable that the Kentland dome remained above sea-level until the end of the Devonian or later."

The geological map of Indiana published by Blatchley[9] in 1904 shows the exposures east of Kentland as Silurian (Niagaran) and the same reference was made in a later map by Logan[10] in 1922.

Green[11] quoted from all of the important references made to the Kentland area up to the time of his report, pointed out the absurdity of Gorby's and Thompson's explanation of the fossils having been blown up from below, and criticized Kindle for not recognizing the Ordovician age of the rocks at Kentland.

Ward,[12] in discussing the road materials of northwestern Indiana, described the Kentland exposures as follows: "This ridge, of Niagara limestone, offers a rather complex problem; but it seems that it is a synclinal fold, much broken in the folding." Ward's conclusion that the entire mass, only part of which is now exposed, was apparently a pre-glacial eminence is supported by the fact that short distances away from the quarry district the drift becomes much thicker.

Foerste[13] was the third geologist to call attention to the Ordovician age of the Kentland outcrops. He correlated the fossiliferous beds with the Black River of New York and listed a number of fossils, referred to later in the present paper, from a ". . . . very fine-grained, brownish-gray limestone having a conchoidal fracture, resembling some phases of the Plattin limestone of eastern Missouri."

Cumings[14] called attention to the Ordovician age of the exposures

[9] W. S. Blatchley, *Geological Map of Indiana* (1904).

[10] W. N. Logan, "Economic Geology of Indiana," *Handbook of Indiana Geology, Ind. Dept. Conserv.*, Part V (1922), map facing p. 796.

[11] G. K. Greene, "On the Age of the Rocks near Kentland, Indiana," *Contr. to Indiana Paleontology*, Vol. II, Part I (1906), pp. 11–17.

[12] L. C. Ward, "Roads and Road Materials of the Northern Third of Indiana," *Ind. Dept. Geol. and Nat. Res., 30th Ann. Rept.* (1906), p. 216.

[13] A. F. Foerste, "Notes on Arctic Ordovician and Silurian Cephalopods," *Denison Univ. Bull.*, Vol. XIX (1921), pp. 277–78.

[14] E. R. Cumings, "Nomenclature and Description of the Geological Formations of Indiana," *Handbook of Indiana Geology, Ind. Dept. Conserv.*, Part IV (1922), pp. 420–49.

near Kentland, and suggested that the structural conditions may have been caused by cryptovolcanic activity.

R. T. Chamberlin[15] referred to the very steeply inclined attitude of the Kentland rocks, as follows: "Some two miles east of Kentland, in the plains of northeastern [northwestern] Indiana, the limestone beds exhibit a very sharp, narrow-crested anticlinal fold whose limbs reach the surprising inclination of over 80°. . . . ." Dr. Chamberlin has indicated in recent discussions and correspondence with the authors that he favors the cryptovolcanic theory of origin for the disturbed condition of the rocks near Kentland.

When Cumings and Shrock[16] showed that the quaquaversal "domes" along the upper Wabash Valley were ancient stromatoporoid and coral reefs (bioherms), they also pointed out that the presence of Ordovocian strata at Kentland, and the deformed and disturbed condition of those strata, precluded a reef origin, and indicated on the other hand a diastrophic origin. As late as 1929, however, Ver Wiebe[17] still confused the Ordovician rocks at Kentland with the Silurian rocks along the upper Wabash Valley.

Shrock and Malott[18] in a very recent paper concluded that, "The structure in these quarries has resulted from intense deformation by both folding and faulting. Rocks are exposed here which in nearby localities, in some cases less than three miles, are, 1,500 feet beneath the surface." The rocks were referred to the Black River–Trenton division of the Ordovician on the basis of a fauna of over twenty species. In spite of this correlation Logan,[19] in discussing the wells of Newton County, cautiously referred to the rocks as "perhaps old-

[15] R. T. Chamberlin, "On the Crustal Shortening of the Colorado Rockies," *Amer. Jour. Sci.* (5), Vol. VI (1923), p. 217.

[16] E. R. Cumings and R. R. Shrock, "The Silurian Coral Reefs of Northern Indiana and Their Associated Strata," *Ind. Acad. Sci. Proc. for 1926* (1927), Vol. XXXVI, pp. 71–85; "Niagaran Coral Reefs of Indiana and Adjacent States and Their Stratigraphic Relations," *Bull. Geol. Soc. Amer.*, Vol. XXXIX (1928), pp. 579–619; "The Geology of the Silurian Rocks of Northern Indiana," *Ind. Dept. Conserv., Pub. No. 75* (1928).

[17] W. A. Ver Wiebe, "Unconformity at Top of Trenton in Lima, Indiana, District," *Bull. Amer. Assoc. Petr. Geol.*, Vol. XIII (1929), p. 689.

[18] R. R. Shrock and C. A. Malott, "Notes on Some Northwestern Indiana Rock Exposures," *Ind. Acad. Sci. Proc. for 1929* (1930), Vol. XXXIX, p. 221.

[19] W. N. Logan, "Sub-Surface Strata of Indiana," *Ind. Dept. Conserv., Pub. No. 108* (1931), p. 450.

er than the Silurian," but the area was left blank on the new geological map of Indiana which appeared late in 1932.

From the above summary of the work that has been done on the exposures near Kentland, it is evident that: (1) the rocks, long referred to the Silurian (Niagaran), are of Middle Ordovician age; and (2) the structural conditions of these rocks, long considered by some geologists to have had the same origin as the "domes" or reefs along the upper Wabash Valley, are in reality the result of crustal deformation involving both folding and faulting.

GENERAL REGIONAL STRATIGRAPHY

The general stratigraphy of northwestern Indiana and northeastern Illinois is shown on Figure 2. To the west, north, and northeast of the quarry district at Kentland, New Albany black shale of Devonian (possibly Mississippian) age is encountered in wells at depths of about 100 feet below the flat glacial plain.[20] The general surface elevation of the wells is about the same. To the east near Goodland, a quarry exposure of Silurian (Niagaran) was reported by Kindle[21] in 1904, but from an examination by the authors of slabs lying about on the surface around the shallow abandoned quarry, and furthermore, in view of the fact that typical Borden (Mississippian) rocks are present only 2 miles farther east, it seems much more likely that the rocks west of Goodland are best referred to the Mississippian.[22] To the south numerous well records suggest the presence of Lower Pennsylvanian sediments. There appears to be some doubt, however, as to whether the records of the wells are reliable for Ashley[23] questioned them and Logan[24] omitted them in discussing the well records of Benton County, but he did include Pennsylvanian sandstones and shales (Pottsville) in the geologic section for that county.

The area in which the Ordovician rocks are exposed appears to be a somewhat elevated rock mound surrounded on all sides by younger

[20] In the following discussion data concerning wells were obtained from Dr. W. N. Logan, *ibid.*

[21] E. M. Kindle, "The Stratigraphy and Paleontology of the Niagara of Northern Indiana," *Ind. Dept. Geol. and Nat. Res., 28th Ann. Rept.* (1904), pp. 413–14.

[22] R. R. Shrock and C. A. Malott, *op. cit.*, pp. 224–25.

[23] *Op. cit.*, pp. 184–91. (The records referred to are included in this report.)

[24] *Op. cit.*, pp. 40–41.

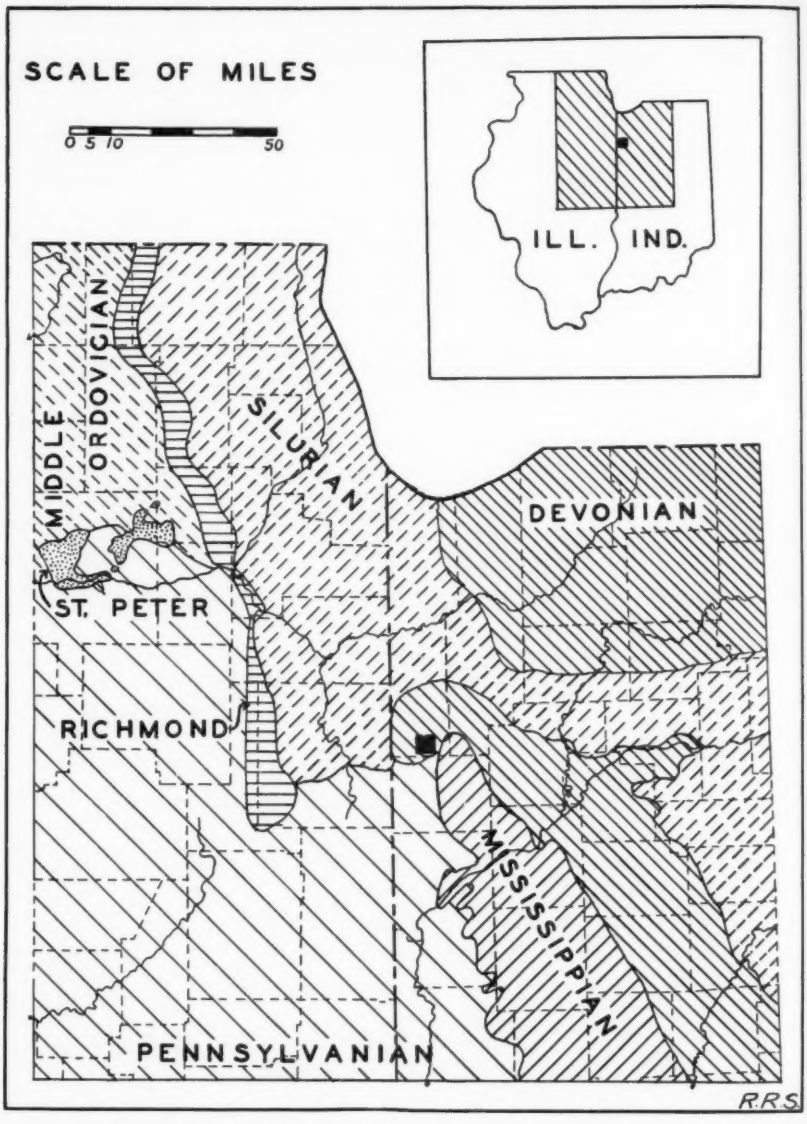


FIG. 2.—Geologic map of northwestern Indiana and northeastern Illinois. The Kentland area is indicated by a small black square. (After the geological map of Illinois by De Wolf [1917] and the geological map of Indiana by Logan [1932] with slight modifications.)

formations. Whether the strata ranging in age from Silurian to Pennsylvanian overlie the Ordovician disconformably, or whether some or all of them are likewise disturbed but concealed beneath the drift, cannot be stated with present knowledge. At the present time the glacial drift effectively conceals the zone where younger formations are in contact with the Ordovician rocks. The nearest rocks of Ordovician age are many miles west of Kentland in northeastern Illinois (see Fig. 2).

DETAILED LOCAL STRATIGRAPHY

The relation of the three quarries in which the exposures may be observed is shown in Figure 1. The sections available in each of the quarries are shown in Figure 5.

MC KEE'S QUARRY

The easternmost of the present quarries is called McKee's Quarry, and is now abandoned. It is a dry, shallow opening about 650 feet long and from 25 to 75 feet wide, with a small hole a little north of the main quarry. Excavation followed the north-south strike of the beds. The strike varies from N. 2° E. to N. 22° W., and the strata dip to the east at an angle of from 58° to 71°. Good cross-lamination along the east side of the quarry shows that the top of the beds is to the east. About 65 feet of evenly bedded gray and buff dolomitic limestones are exposed. Numerous fossils occur along the bedding planes of the fairly thin beds.

In about the middle of the quarry along the east side cone-shaped, slicken-sided surfaces are abundant, showing slight displacements both along the bedding and across it. These are the so-called "cone-in-cone" structures mentioned by the earlier writers. The present writers have been informed by Dr. W. H. Bucher[25] that somewhat similar structures are present in the Wells Creek Basin, in western Tennessee, which is considered by him to be of cryptovolcanic origin. He wrote the following concerning them.

> The curious cone-in-cone-like fracture pattern, which I like to refer to as "shatter cones," looks like that which I found in the central area of Wells Creek Basin in Tennessee. It differs from it in being merely a curious pattern on fracture planes, chiseled like a bas-relief. The shatter cones in Wells Creek Basin,

[25] Personal communication.

like their prototype in the Steinheim Basin of Germany, is a sort of fracture cleavage representing inter-penetrating cones into which the rock could easily be split by gentle tapping with the hammer. Both phenomena seem to be, however, closely related.

The following fossils have been found in this quarry:[26] *Dalmanella testudinaria* (Dalman) (Gorby), **Leperditella persimilis* (Ulrich), **Leperditia fabulites* (Conrad), *Poterioceras kentlandensis* Greene

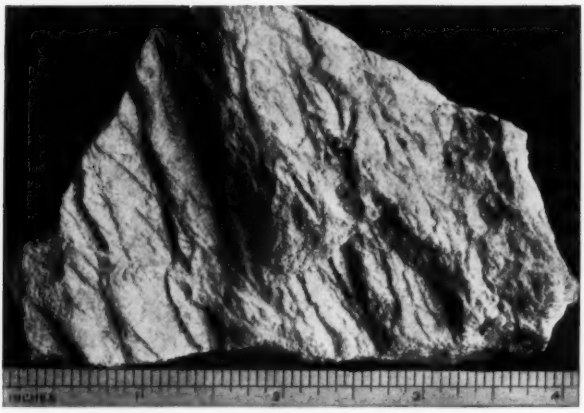


FIG. 3.—Specimen showing shearing planes in the sandstone

(Greene), **Rhinidictya mutabilis* (Ulrich), **R. paupera* (Ulrich), **Tetradium cellulosum* (Hall), and **Zygospira recurvirostris* (Hall). This fauna establishes the age of the strata in the McKee Quarry as Black River.

MEANS QUARRY

The westernmost quarry, also abandoned, is known locally as the Means Quarry. It is about 150 feet long in an east-west direction and 70 feet wide in a north-south direction. Here also quarrying has followed the strike which is generally east-west. (See Fig. 1.)

The strata dip to the north from 51° to 66° and the strike varies

[26] Those species marked by an asterisk have been found and identified by Mr. Shrock. The others have been reported by the author whose name appears second after the species name.

Detailed sections taken at various places in the three quarries will be given in a paper, now in preparation, in which the fauna will be described and figured.

from E.-W. to S. 57° W. The general similarity of this section, both in thickness and lithology, to the one in the McKee Quarry, and the position of the fossils along the bedding planes indicate that the top of the beds is to the north.[27]

"Shatter cones" are common and numerous fractures make it difficult to obtain a very large piece of the rock. Along the east end of the quarry a system of fractures, whose plane is normal to the bedding and strike, occurs as stated by Kindle.[28] The rock comes to the surface several hundred feet east of the quarry, and appears to lie close to the surface north, west, and south of the quarry for the ground is covered with numerous small slabs of rock and the soil is lighter in color than the black glacial soil.

The following species were collected from the Means Quarry:[29] *Beatricia* n. sp., *Bumastus milleri* (Billings), *Ceraurus dentatus* Raymond and Barton, *Cryptophragmus antiquatus* Raymond, *Escharapora angularis* Ulrich, *E. recta* Hall, *E. suberecta* (Ulrich), *Eurychilina ventrosa* Ulrich, *Helopora mucronata* Ulrich, *Krausella arcuata* Ulrich, *Leperditella canalis* Ulrich, *L. persimilis* Ulrich, *Leperditia fabulites* (Conrad), *Orthis tricenaria* Conrad, *Primitiella simulans*

[27] The numerous fossils which were collected from this quarry came mainly from the upper side of the layers. The fossils themselves are firmly imbedded in the limestone, and are separated from the overlying layer of limestone by a very thin shale layer. The shale layer produces a zone of weakness along which the beds separate easily.

It may be suggested that the change from calcium carbonate precipitation to an influx of mud buried the organisms living on the bottom before the scavengers could chew them up, because the remainder of the limestone bed is to a large extent composed of pulverized shell fragments. Hence the side of the limestone layer having the fossils imbedded in it and in turn covered by shale would represent the top of the bed. This criterion cannot be applied universally, perhaps, but certainly it is suggestive, especially when a number of layers show fossil remains on only one side.

Furthermore, not only are most of the convex shells found on the surface of the layers convex upward, but those included within the layer show the same position. The broken shell fragments found in numerous concavities on the surface of some of the beds indicate current action along the bottom. This being the case, then the stable position for convex shells will be convex upward, and the side of the bed showing the shells with their convex sides up will be the top side.

All evidence points to the conclusion that the top of the beds is to the north and hence the strata are only steeply inclined—not overturned.

[28] *Ind. Dept. Geol. and Nat. Res., 28th Ann. Rept.* (1904), p. 43.

[29] Most of the species were identified by H. L. Lloyd who figured and described them in an unpublished M.A. thesis at the University of Wisconsin.

Ulrich, *Pterygometopus eboraceus* Clarke, *Rafinesquina alternata* (Emmons), *R. minnesotensis* (N. H. Winchell), *Rhinidictya mutabilis* (Ulrich), *Rhynchotrema minnesotense* (Sardeson), and *Zygospira recurvirostris* (Hall). This is a typical Black River (Decorah) assemblage and correlates accurately with the Minnesota fauna described by Ulrich and others.[30]

MC CRAY'S QUARRY

The largest of the three quarries, and the only one which is active at the present time, was formerly called the McCray Quarry, but is now commonly referred to as the Kentland Quarry. It is being operated by the Newton County Stone Company. In the summer of 1932 the opening was roughly rectangular in shape, being about 900 feet long north and south and 450 feet wide east and west. The depth to which the stone has been removed varies from 35 to 70 feet.

This quarry offers a very interesting and perplexing set of structural and stratigraphical problems. Everywhere the rocks exhibit abundant evidence of having been subjected to intense deforming stresses. Dips vary from nearly horizontal (rare) to vertical, and in a few places overturning has taken place. It is believed, however, that most of the inclined beds are top side up. Bedding faults, brecciated zones parallel to and cutting across the bedding, "shatter cones," and other fracture phenomena are abundant showing that the rocks yielded by fracture rather than by folding. Folds are rare in the quarry. Sandstones, shales, and limestones were involved in the deformation and each failed somewhat differently under stress. The general fault mosaic, as shown in Figure 4,[31] and the confusion

[30] *Paleontology of Minnesota*, 1892, 1895, 1897, etc.

[31] On this map the strike-dip symbols show the inclination of the beds and faults in respect to a horizontal plane, but only in the cases of continuous sections do the figures indicate the true dip of the beds, for elsewhere in the quarry it was not possible usually to tell tops and bottoms of beds. Unless otherwise indicated the faults are vertical or steeply inclined. Many of the smaller faults parallel to or across the bedding are not shown, because displacement along them is usually a matter of only a few inches. There are numerous fractured zones some of which may represent true faults whereas others almost certainly represent fracture cleavage. The large area, indicated as "covered," surrounding the rim of the quarry and comprising most of the quarry bottom, is covered by crushed rock or washed in glacial drift and leaves many gaps where information would be of the greatest value. When these gaps are filled some of the interpretations on the present map may be shown to be incorrect. The map is based on data obtained during a number of visits over a period of five years.

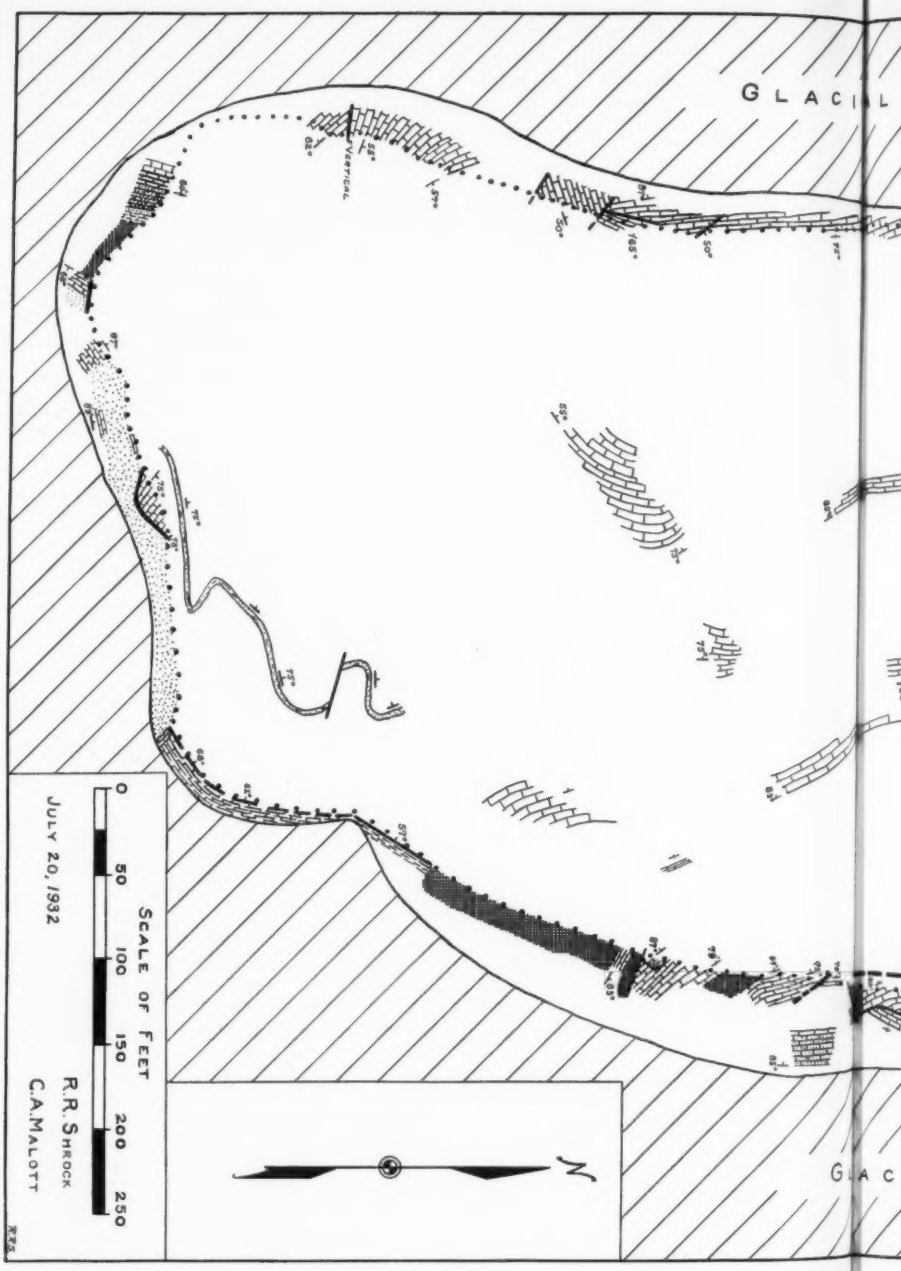
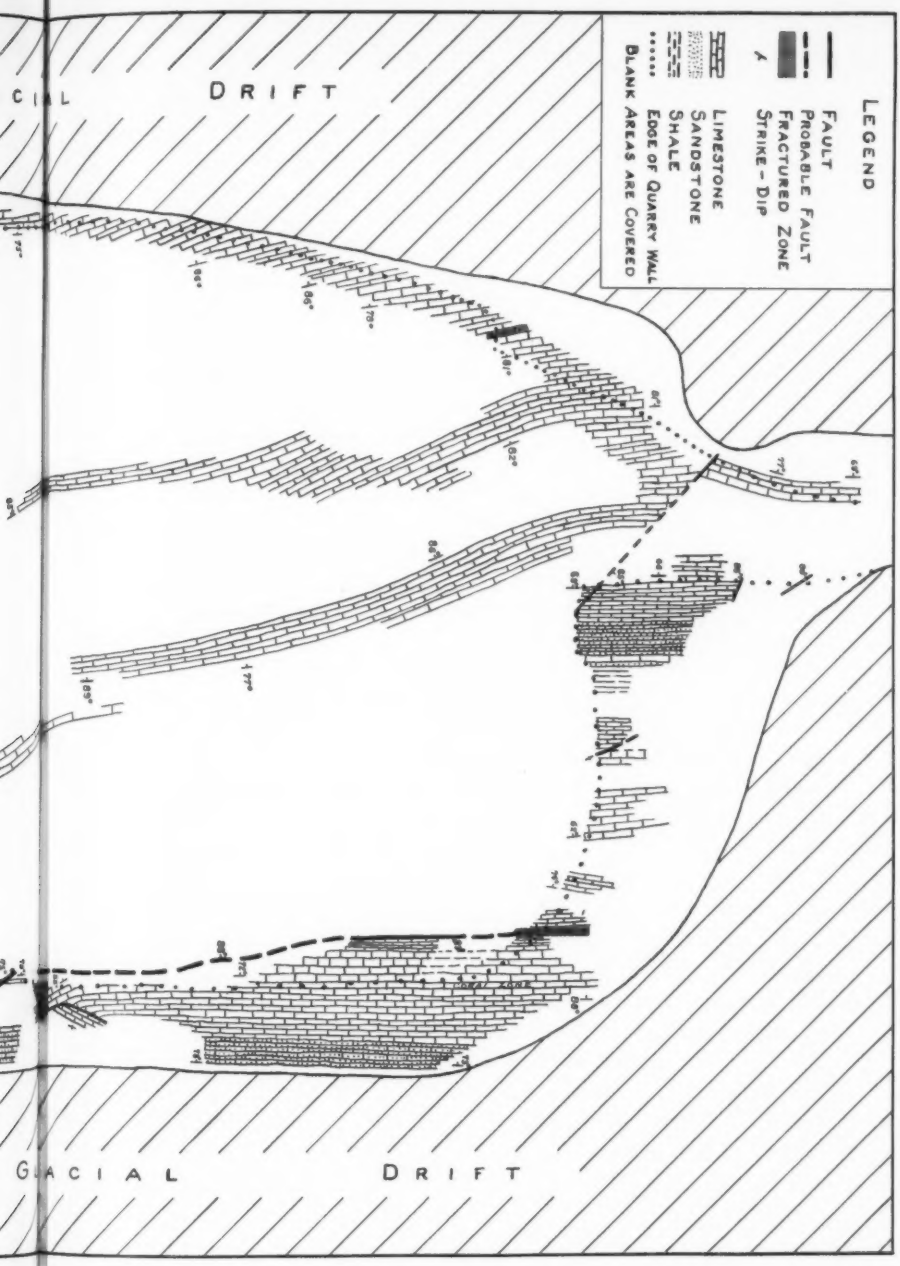


FIG. 4.—Map of the McCray quarry, 3 miles east of Kentland, Indiana, showing the areal geology, struc and ext ly conceals the underlying bedrock. See text for further information concerning the map.



structure and extent of exposure of the rocks. Much of the quarry floor is covered with crushed rock which effective-

of different rock types show why Collett[32] nearly fifty years ago wrote: "This quarry is a mystery."

A report much more detailed than the present one would be needed to consider each of the fault blocks individually. The following discussion will confine itself to a consideration only of such blocks as exhibit continuous sections which can be assigned to a definite stratigraphic position on the basis of fossils, lithology, or other important characteristics.

Sandstone.—A white to gray quartz sandstone is exposed in the south wall of the quarry, and on the surface southward from the edge of the quarry for 10 or 15 feet (see Fig. 4). The lower part of the quarry face is concealed beneath talus and the upper surface passes southward under the glacial drift. To the east and to the west the sandstone gives way to a light-colored, fine-grained argillaceous limestone. Whether the contact is a fault or a sedimentary one cannot be determined, since it cannot be seen. The limestone is so intensely fractured that the bedding is either very obscure or entirely obliterated. It seems to be always closely associated with the sandstone and in one section apparently overlies the main sandstone mass.

A screen analysis of the sand was attempted, but the rock was found to be so intensely fragmented that the results were without significance. The grains when unbroken are well rounded and frosted and many show secondary enlargement. It is somewhat uncertain as to how much of the frosting or roughened condition of the surface of the grains is original and how much was imposed on the grains as a result of shearing during the deformation. Some light may be thrown on this question by the occurrence in an overlying limestone of numerous small lenses of quartz sand composed of beautifully rounded and frosted grains, very likely derived from this sandstone or from the same general source long before the deformation of the sandstone. The grains of the sandstone range in size from .1 mm. to .5 mm. The larger grains show the better rounding.

Filling the pores and comprising a considerable portion of the sandstone in its present condition is finely pulverized quartz, which closely resembles a white powder or flour. Under the microscope

[32] *Op. cit.*, p. 59.

this powder is seen to consist of very small, angular fragments of translucent or transparent quartz. Much of the powder was undoubtedly derived from the grinding together of the grains during the deformation. A screen analysis showed more than 11 per cent which was caught on the 200-mesh screen. Many of the larger grains are cracked, and many others have been broken into bits, so that some of the larger fragments show part of their surface rounded and frosted and the other part conchoidally fractured and with a glassy surface. It is obvious that this sandstone has undergone intense crushing—so intense in fact that scarcely a grain of any size has escaped fragmentation. Many of the grains have literally been ground to dust.

As a result of the deformation the sandstone breaks into polyhedral blocks bounded by flat surfaces along which occurs granulated, powdery quartz. These blocks, however, can be disintegrated easily into loose sand with a light blow from a hammer. The cleavage planes do not represent schistosity, but rather fracture cleavage or planes of slipping along which the sand has been ground to a very fine condition (see Fig. 3).

A microscopic examination of the detrital minerals of the sandstones showed quartz, feldspar (both orthoclase and plagioclase), zircon (small, very well-rounded grains), garnet, and tourmaline. All but quartz are rare. Flat discoidal concretions, composed of sand cemented together with iron oxide, are numerous and are found scattered over the surface of the loose sand. They range in diameter from 1 to 4 inches. Some of the sand is firmly cemented, being almost quartzitic. This cementation was apparently accomplished by circulating ground waters.

The well-rounded and frosted condition of the quartz grains, and the range in grain size (.1–.5mm.), agree fairly closely with that which Udden[33] reported from the St. Peter sandstone found in a well at Kankakee, Illinois. Furthermore, the close association of this sandstone with limestones of Black River age in general, and with a light buff, argillaceous limestone which immediately overlies it and contains *Leperditia fabulites* and *Rafinesquina minnesotensis*, lends support to its correlation with the St. Peter sandstone.

[33] J. A. Udden, "Some Deep Borings in Illinois," *Ill. Geol. Surv. Bull. 24* (1914), pp. 50–55.

In the southeast corner of the quarry, about half way up the slope, Professors Stark and Lamey, from Northwestern University, discovered a fossil zone in the sandstone. The fossils occur in a somewhat finer-grained phase of the sandstone and are preserved mainly as casts. The fauna, identified by Mr. G. O. Raasch, consists of: *Endoceras* sp., *Liospira* sp., *Modiolopsis* (2 species), *Orthodesma* sp., *Sphenolium* n. sp., and *Triptoceras* sp.

Since the bedding in the sandstone is completely obliterated in almost the entire exposure, the thickness of the formation could not be determined. In two places the contact of the sandstone with contiguous formations was seen. Elsewhere the contact zones are always obscured by fracturing or mashing of the sandstone and the adjacent rock.

In about the middle of the exposure, where a small ravine cuts into the sandstone, a zone of greenish, flaky shale is exposed. It is very closely folded into several small anticlines and synclines and is surrounded on all sides and above by sandstone, but its base is not exposed. A bed of oölitic chert is closely associated with this shale zone. A similar chert band is also present along the east edge of the sandstone exposure. The greenish shale and the oölitic chert are strongly suggestive of the contact zone between the St. Peter sandstone and the underlying Shakopee dolomite as reported by Lamar.[34]

In the summer of 1929 a considerable thickness of dolomite was found to lie north of the sandstone and, the authors believe, on top of it. This sequence, which graded from sandstone through shaly dolomite into dolomitic limestone, had a strike of N. 55° W. and dipped 75° northeast. It has since been almost entirely removed by quarrying operations (see Fig. 5, column 2). If this section is the basal portion of the Chazy overlying the St. Peter, and the shale and oölitic chert are at the contact between the St. Peter and the Shakopee or Oneota, then the full thickness of the St. Peter is included in the exposures along the south side of the quarry, unless part of the formation has been faulted out.

From the sedimentary characteristics of this sandstone and from the relations it exhibits to formations thought to lie below and above,

[34] J. E. Lamar, "Geology and Economic Resources of the St. Peter Sandstone of Illinois," *Ill. Geol. Surv. Bull. 53* (1928), p. 21.

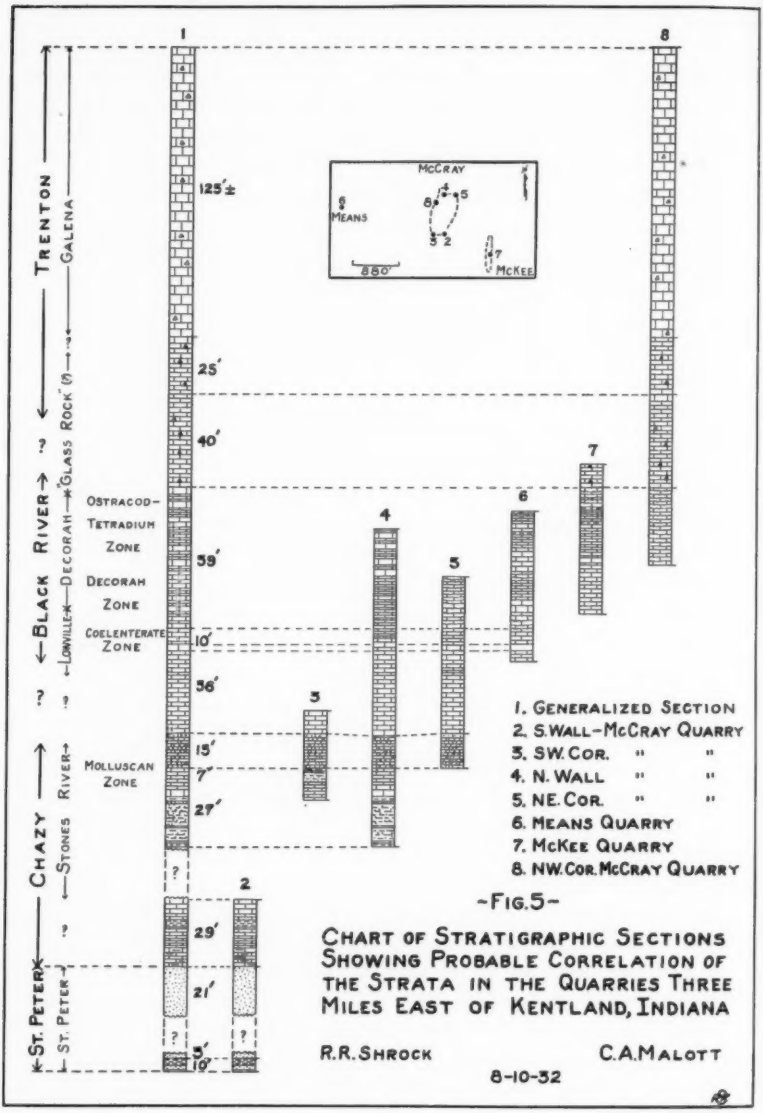

TRENTON
GALENA
BLACK RIVER
GLASS ROCK
DECORAH
LOWVILLE
CHAZY
STONES RIVER
ST. PETER
ST. PETER
OSTRACOD-TETRADIUM ZONE
DECORAH ZONE
COELENTERATE ZONE
MOLLUSCAN ZONE
125'±
25'
40'
39'
10'
36'
15'
7'
27'
29'
21'
5'
10'
1
2
3
4
5
6
7
8
McCRAY
MEANS
McKEE
880'
1. GENERALIZED SECTION
2. S. WALL-McCRAY QUARRY
3. SW. COR. " "
4. N. WALL " "
5. NE. COR. " "
6. MEANS QUARRY
7. McKEE QUARRY
8. NW. COR. McCRAY QUARRY
-FIG. 5-
CHART OF STRATIGRAPHIC SECTIONS SHOWING PROBABLE CORRELATION OF THE STRATA IN THE QUARRIES THREE MILES EAST OF KENTLAND, INDIANA
R. R. SHROCK
C. A. MALOTT
8-10-32

FIG. 5

the authors are of the opinion that it represents the St. Peter sandstone of adjacent states to the west and northwest.

Shale.—A true shale formation is exposed in the southeast corner of the quarry (see Fig. 4). The outcrop appears to be bounded by faults, and until very recently was not exposed.

The rock is a dark blue to chocolate-colored or dark gray, massive shale with considerable calcareous material and without grit. Owing to the weathered condition of the rock, especially aided by the high degree of fracturing, it is almost impossible to obtain a hand specimen of any size. Under weathering conditions the shale has a tendency to break into smaller and smaller chips and fragments, but does not seem to slake into a mud readily. Along the south edge of the exposure several thin layers of impure, dirty-gray limestone are standing in a nearly vertical position, but bedding is not apparent in the shale proper, hence its thickness could not be determined. Its minimum thickness, however, is certainly not less than 10–15 feet. It seems very likely, however, that the thin limestone layers are part of the shale formation, and that the bedding in the shale is parallel to the former. If such is the case the shale is thicker than 15 feet. The exposure ends to the north against a very much fractured zone of light-colored dolomitic limestone. On the south side the shale is mashed together with broken, heavy layers of blue, fine-grained limestone, and the contact is not discernible. From a knowledge of previous conditions in that part of the quarry where the shale is now exposed, it seems very likely that the present surface of the shale is a fault surface, and it is so indicated on the map (Fig. 4).

The age of this shale formation is uncertain. It cannot be seen anywhere in actual sedimentary contact with any other formation. Furthermore, in spite of very careful search on several different occasions, not a vestige of a fossil could be found. Logan[35] listed several well records from Jasper County, at localities some 20 miles northeast of the quarry district, in which a brown, blue, or chocolate shale, several hundred feet thick, is present immediately above the "Trenton." This is the so-called "Utica" shale of the older reports, and lies between the Trenton and the Richmond shales in northern Indiana. Whether the shale formation at Kentland represents part of the

[35] *Ind. Dept. Conserv., Pub. No. 108* (1931), p. 374.

"Utica"; whether it is a higher formation; or whether it is lower in the stratigraphic column, must be left unanswered until further data are available.

Limestone Sequences.—Several types of limestone are found in the McCray Quarry. They vary widely in character and apparently represent distinct formations. Fossils are numerous at certain horizons. All of the limestones appear to be of Ordovician age, comprising a sequence lying between the St. Peter sandstone below and the "Utica" shale or Richmond shale above.

North Wall of Quarry.—Several fairly complete sequences of limestone may be studied in the present quarry. One of these is found along the north wall of the quarry just east of the ramp (see Fig. 4). The beds have a general north-south strike and dip west at an angle of 65° to 75°. Most of the convex shells have their convex sides toward the west indicating that the beds are right side up, and this is corroborated by both the stratigraphy and the succession of fossils. The section shown in column 4, Figure 5, was measured across the upturned edges of the steeply dipping strata.

East of the measured section the bedding becomes quite obscure and the rock is highly factured, being brecciated in several places along faults. Since it is not certain whether the rock is a continuation of the measured section, it is not included. This highly fractured and weathered zone is over 80 feet wide and because of a partial covering on the surface back from the quarry wall it is not possible to determine whether the entire thickness is one continuous sequence or whether it is broken by faults.

There are several fossil zones in the measured sequence. A *Tetradium*, too poorly preserved for accurate identification as to species, along with some pelecypods, is common in the upper part. A very large fauna, chiefly molluscan in character, was collected from the lower part. The following list includes the common species:[36] *Actinoceras* sp. (cf. *libanum* Foerste), *Ambonychia* n. sp., *Bucania halli* Ulrich and Scofield, *Ceraurus pleurexanthemus* Green, *Clathrospira subconica* (Hall), *Clionychia* n. sp., *Clisiospira occidentalis* Whitfield, *Ctenodonta* cf. *levata* (Hall), *C. logani* Salter, *Cyrtodonta huronensis*

[36] The writers are very grateful to Mr. Gilbert O. Raasch, Curator of the Geological Museum, University of Wisconsin, who identified most of the species in the following list after a careful preliminary study.

Billings, *Valcouria deflecta* (Conrad), *Eccyliomphalus undulatus* Hall, *Eotomaria* cf. *labiosa* Ulrich, *Holopea similis* Ulrich and Scofield, *Hormotoma gracilis angustata* (Hall), *Hyolithes baconi* Whitfield, *Isotelus gigas* de Kay, *Kentlandoceras shrocki* Foerste,[37] *Leperditia fabulites* (Conrad), *Liospira* cf. *abrupta* Ulrich and Scofield, *Liospira* n. sp. (near *angustata* Ulrich and Scofield), *L. conradana* Ulrich and Scofield, *L. oweni* Ulrich and Scofield, *L. perangulata* Ulrich and Scofield, *L. serrulata* (Salter), *Pholidops trentonensis minor* (?) Winchell and Schuchert, *Phragmolites grandis* (Ulrich), *Doleroides perveta* (Conrad), *Pterotheca attenuata* (Hall), *P. expansa* (Emmons), *Rafinesquina minnesotensis* (N. N. Winchell), *Rhynchotrema minnesotense* (Sardeson), *Salterella billingsi* Safford, *Scolithus* sp., *Stenotheca* sp., *Strophomena incurvata* (Shephard), *Tetranota wisconsinensis* Whitfield, *Thaleops ovatus* Conrad, *Triptoceras* n. sp. (Large form), *Triptoceras* n. sp. (Small form), *Vanuxemia rotundata* (Hall), *Vanuxemia* n. sp. (cf. *niota* [Hall]) *Whitella* n. sp., *Zygospira saffordi* (Winchell and Schuchert).

The fauna just listed belongs in the base of the Middle Ordovician and is equivalent to the Stones River fauna of Alabama, Tennessee, and Kentucky;[38] "Stones River" of Minnesota;[39] Platteville of the Upper Mississippi Valley; Upper Chazy and Lower Black River (Lowville or "Birdseye") of northwestern New York and "Black River" (Leray) of Ontario, Canada.[40]

[37] Dr. A. F. Foerste very kindly examined some cephalopod material from the Kentland quarries and wrote concerning one specimen, "Your smaller specimen from the McCray Quarry I have numbered M-6. It is a new species and belongs to a new genus of which I have three species.

1. From Black River at St. Joseph Island, Lake Huron.
2. From Black River of Kingstown, Ontario, Canada.
3. From Kentland, Indiana, your specimen M-6.

I could call this specimen Kentlandoceras schrocki, or Kingstonoceras schrocki. In the first case your specimen would be the genotype. In the second case the Kingston specimen would be the genotype, and yours would be referred to the same genus."

[38] C. Butts, "Geology of Alabama—The Paleozoic Rocks," *Geol. Surv. Ala., Special Report No. 14* (1926), pp. 119–31; R. S. Bassler, "The Stratigraphy of the Central Basin of Tennessee," *Tenn. Geol. Surv. Bull. 38* (1932), pp. 49–115.

[39] E. O. Ulrich, *et al.*, "Geology of Minnesota," *Geol. and Nat. Hist. Surv. Minn.*, Vol. III, Part 2 (1897), pp. cv–cxxvii.

[40] R. S. Bassler, "Bibliographic Index of North American Ordovician and Silurian Fossils," *U.S. Nat. Mus. Bull. 92*, 2 vols. (1915); W. A. Johnston, "Geology of Lake Simcoe Area, Ontario, Brechin and Kirkfield Sheets," *Geol. Surv. Can. Summary Rept. 1911* (1912), pp. 253–61.

Thirty-four feet above the base of the section is a unique formation which should be identified readily and easily elsewhere because of the stringers of lime-bound quartz sand. This clastic sand comprises from 30 per cent to 45 per cent of the rock and consists almost entirely of well-rounded and frosted quartz grains, which range in size from .1 mm. to 1 mm. Most of the grains are between .2 mm. and .4 mm in diameter.

The individual sand grains in this unit show several important and significant features. Almost all of the grains are well rounded and are frosted, or are fragments coming from the fracturing of such grains. Furthermore, many of the grains regardless of their size show undulatory extinction under crossed nicols. This phenomenon indicates a strained condition in the quartz, probably imposed upon the grains when the limestone layers were deformed. It appears quite likely, judging from the sedimentary and lithologic characteristics, that this clastic sand was derived from the St. Peter sandstone.

This interesting unit of sandy limestone is found in three other places in the quarry as shown in the map, Figure 4. The beds appear to have been duplicated by faulting, since it seems extremely unlikely that such a unique formation, together with its contiguous strata, would appear more than once in a normal limestone sequence. Wherever seen, some of the layers in this unit contained large numbers of *Rafinesquina minnesotensis*.

Southwestern Corner of Quarry.—One of the isolated occurrences of the sandy limestone is found in the extreme southwestern corner of the quarry. The section shown in column 3, Figure 5, duplicates part of the sequence along the north wall of the quarry and was measured across the upturned edges of the steeply dipping beds. The beds have a strike of N. 15° E. and dip west at an angle of about 60°.

Northeastern Corner of Quarry.—Parts of the two sequences already discussed are duplicated in the northeast wall of the quarry. Recent excavation east of the east wall has revealed the same lime-bound, sandy limestone observed elsewhere in the quarry. The shaley unit beneath is not exposed, apparently because it was dug out by the glacier as it passed, for the lime-bound layers form low *roches moutonées*, and the smoothed rock surfaces slope steeply to the east under the drift. The beds strike almost north and south and dip to

the west from 73° to 89°. Attention should be called to the fact that this sequence of beds dips about the same amount, and in the same direction, as the sequence along the northern wall of the quarry. Furthermore, the beds appear to be right side up in both sequences. The duplication, therefore, must be due to faulting rather than to folding. Data are not available, however, for locating either the position or the inclination of such a fault. The north-south, eastward-dipping fault may have some significance in this respect. The sequence, from the fault just mentioned to the edge of the glacial drift along the east side, is shown in Figure 5, column 5.

The basal beds of the sequence are similar to the sandy limestone of column 4, Figure 5. Near the top of the sequence there occurs a very significant coelenterate fauna consisting of *Cryptophragmus antiquatus* Raymond and *Tetradium carterensis* Bassler, together with a new species of *Beatricia* and *Leperditia fabulites* (Conrad). Immediately overlying the section, and possibly continuous with it, is a buff, somewhat crystalline dolomite full of a poorly preserved *Tetradium*.

Northwestern Corner of Quarry.—A continuous section of considerable thickness is shown on the map, Figure 4, in the northwest corner of the quarry and along the western side. It was not possible to measure the section in detail because of the lack of exposures in the bottom of the quarry. Recently, however, extensive excavation south of the incline has revealed considerable concerning the character and attitude of the strata in the northern half of the quarry. It seems that there is a sequence of buff magnesian limestones of uneven texture alternating with fine-grained, dense bluish limestone, of approximately 150 feet in thickness in the northwestern part of the quarry; south of the N.W.–S.E. fault, which separates it from the sequence to the north.

There seems to be no break in the succession along the west side of the quarry except at one place where a bedding fault is present. The displacement, however, seems to be small and there is no evidence of the thickness having been affected. This succession is shown as column 8 in Figure 5. The following fossils were found in the basal beds of the sequence: *Hormotoma gracilis* (Hall), *Isotelus gigas* de Kay, *Leperditia fabulites* (Conrad), *Leperditella tumida*

Ulrich, *Strophomena* sp., *Subulites* sp., and *Zygospira recurvirostris* (Hall). *Columnaria* and several species of pelecypods were found in about the middle of the sequence. The lithology of the upper two-thirds of the sequence suggests that of the Galena dolomite of southwestern Wisconsin.

THE GENERALIZED STRATIGRAPHIC COLUMN

Column 1 in Figure 5 shows the generalized stratigraphic column of the rocks exposed in the three quarries. It was constructed by piecing together the fragmental sequences found in those quarries. Obviously there are some gaps that cannot be evaluated either as to thickness, lithological character, or faunal content because of lack of exposures. Future excavation may reveal missing strata and perhaps somewhat revise the present column.

The St. Peter Sandstone.—The sandstone exposed along the south wall of the McCray Quarry is correlated with the St. Peter sandstone of the Upper Mississippi Valley on the basis of: (1) stratigraphic relations to overlying and underlying formations; and (2) sedimentary and lithological characteristics.

This formation appears to have a greenish shale, several feet thick, at or near its base. Associated with this shale is some oölitic chert. These suggest the contact zone between the St. Peter sandstone and the underlying Shakopee (or Oneota) dolomite. Upward the sandstone gives way to a series of alternating shaly dolomites, dolomitic shales, and fairly heavy-bedded dolomitic limestones, which apparently represent the basal phase of the overlying Chazy division of the Ordovician. Since no continuous exposure from base to top is available, the complete thickness of the sandstone cannot be determined at present. At least 25 feet are probably present.

The Chazy–Black River Limestone Sequence.—A gap of unknown thickness and lithology is present in the generalized column between the 30-foot sequence of limestones and shales immediately overlying the sandstone and the main mass of the Chazy–Black River sequence. The lowest strata above this gap comprise a series, over 20 feet thick, of argillaceous dolomites overlaid by sandy shales. This unit, which is not fossiliferous, is in turn overlaid by a very fossilifer-

ous zone, 12 feet thick, of alternating beds of bluish-gray, fine-grained dolomite with rough, irregular fracture and dense, brittle, semi-lithographic limestone with smooth conchoidal fracture. A fauna of over fifty species was collected from this general horizon, and establishes its age as Chazy and very early Black River, equivalent to the Stones River of Alabama, Tennessee, Kentucky, and Minnesota; the Platteville of the Upper Mississippi Valley; the Lower Black River (Lowville or "Birdseye") of northwestern New York; and the "Black River" (Leray) of Ontario.

Overlying the molluscan zone just described is a unique formation of about 15 feet in thickness. It consists of fairly thin beds of dense, bluish-gray, fine-grained limestone alternating with somewhat heavier beds of buff dolomitic limestone. The fine-grained layers are characterized by numerous thin stringers and lenses of lime-bound, quartz sand arranged more or less parallel to the bedding planes. This clastic quartz is composed of well-rounded and frosted grains and makes up from 30 per cent to 45 per cent of the layers in which it occurs. A few fossils occur at the base of this unit where it grades into the underlying fossiliferous zone.

The next 36 feet in the general section comprise a sequence of fairly heavy-bedded gray to buff, earthy dolomitic limestones which are but sparingly fossiliferous. This unit breaks down into a dirty dolomitic sand when exposed to prolonged weathering.

One of the most interesting faunas of the entire column comes immediately above the barren 36-foot unit. This small assemblage is concentrated mainly in a 2–3-foot bed at the base of a generally fossiliferous zone about 10 feet thick. The rock of the unit as a whole is mainly a dark-colored, fine-grained limestone, but the basal bed containing the important fauna is little more than a mass of beautifully preserved corals and stromatoporoids. Of unusual interest are three species: *Cryptophragmus antiquatus* Raymond, *Tetradium carterensis* Bassler, and a new species of a *Beatricia*-like stromatoporoid. All of the species occur in great profusion. So far as is known, *Cryptophragmus antiquatus* has been reported and figured from only two other general localities on the North American continent. Raymond, who first described the genus, reported this form from strata equivalent to and just below the Lowville in Quebec,

Ontario, and near Clayton, New York.[41] Butts[42] recently reported the same species from Alabama, where it occurs, along with *Tetradium cellulosum* Hall, in beds equivalent to the Lowville ("Birdseye") of New York. These beds come above strata of Stones River age in the Chickamauga limestone. *Tetradium carterensis* Bassler, a new species recently reported from the Carters limestone (basal Lowville) of Tennessee[43] is found associated with *Cryptophragmus* in the McCray Quarry. Finally, a new species of a *Beatricia*-like stromatoporoid is also found in great numbers not only in the McCray Quarry, but also in the Means Quarry. In the latter quarry it is associated with *Cryptophragmus*, but *Tetradium* is absent. It is on the basis of the two species of stromatoporoids that the "coelenterate zone" in the northeast corner of the McCray Quarry is correlated with a similar zone in the Means Quarry (see general section, Fig. 5). It is apparent then that the "coelenterate zone" of the general section is of very early Black River age, and above the Stones River fauna.

Overlying the unit with *Cryptophragmus* is a thick sequence (about 100 feet) of quite thin-bedded, dense, brittle, dark-blue to chocolate-colored, semi-lithographic limestone, which alternates with occasional heavier layers of buff, somewhat coarser-textured dolomite. In the Means and McKee quarries, a fauna of over 25 species was collected from the shale-covered, upper surfaces of several of the limestone layers. This fauna was found in the lower 30 feet of the sequence, and is correlated with the Decorah division of the Black River of Minnesota.[44] It represents, however, a higher horizon in the Black River than the *Cryptophragmus* zone.

The upper 70 feet of this unit are not very fossiliferous, but have at their base a zone of poorly preserved *Tetradium;* and either at the same horizon or a short distance above or below is a zone of fossils in which ostracods are abundant. There is some doubt as to just how the fragmental sections may be pieced together in this part of

[41] P. E. Raymond, "A Beatricia-like Organism from the Middle Ordovician," *Can. Geol. Surv. Mus. Bull. No. 5,* Geol. Ser. No. 21 (1914), pp. 1–10, Plates.

[42] C. Butts, *op. cit.,* p. 125.

[43] R. S. Bassler, "The Stratigraphy of the Central Basin of Tennessee," *Tenn. Geol. Surv. Bull. 38* (1932), pp. 214–15.

[44] R. S. Bassler, "Bibliographic Index of North American Ordovician and Silurian Fossils," *U.S. Nat. Mus. Bull 92,* 2 vols. (1915).

the general section, but it is believed that the *Tetradium* zone and the ostracod horizon belong at about the same general level, but some distance above the Decorah fauna. Both zones apparently belong below the true "Glass Rock" fauna of southwestern Wisconsin. Since, however, the rock containing the two zones just mentioned has the lithology of the so-called "Glass Rock" of Wisconsin, and also since it occupies a position stratigraphically above the Decorah fauna, it seems probable that the upper 70 feet, more or less, of the 100-foot unit may represent roughly that stratigraphic level. The faunas are nearer Decorah than "Glass Rock" in character.

Trenton (Galena) Dolomite.—Typical "Glass Rock" lithology gives way, in the overlying 25-foot unit, to a buff, somewhat coarser-grained dolomitic limestone, and this in turn to buff, irregular-textured granular dolomite. This 25-foot unit is fairly well bedded, has rather even texture, and has scattered chert nodules throughout. Owing to the fact that it furnished no fossils its stratigraphic position is not clear, but it appears to occupy a zone transitional between the underlying "Glass Rock" and the overlying Galena.

As stated above the 25-foot transitional unit is overlaid by buff, porous, granular dolomite with quite uneven texture, closely resembling the typical Galena dolomite of southwestern Wisconsin. The beds are fairly heavy, and numerous chert nodules occur throughout the sequence both in the beds and along the bedding planes. Only a few poorly preserved fossils were found and they are not diagnostic. The thickness of this unit, judging from what can be seen on the map, Figure 4, and from what measurements could be made, must approximate 125 feet, but such a figure must be considered tentative pending further data as excavation proceeds to the west and south. This thick unit is considered by the authors to be generally equivalent to the Galena dolomite of the Upper Mississippi Valley.

The Shale.—In the general section no disposition is made of the 15 or more feet of light, chocolate-colored shale which is exposed in the southeastern corner of the McCray Quarry. It has yielded no fossils and cannot be seen in sedimentary contact with any contiguous formations, hence its age and position are extremely uncertain. It seems unlikely that it belongs anywhere in the sequence just de-

scribed, though such a possibility cannot be dismissed; nor does it seem likely that it occupies a position beneath the St. Peter sandstone, but again this statement cannot be proved. The other possibility is that it may represent the so-called "Utica" shale reported in some of the nearby wells. Because of the uncertainty of its position it is not shown on the general section.

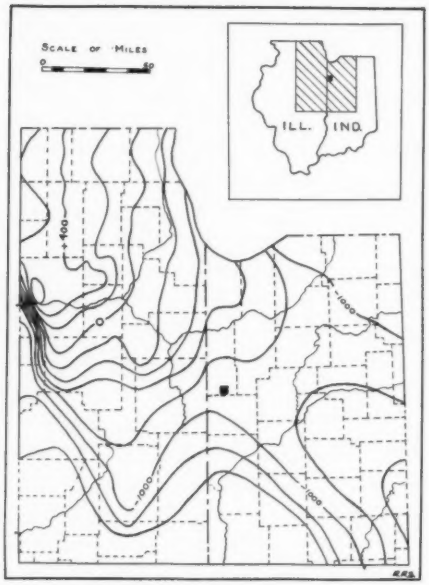


FIG. 6.—Map showing the structure of the top of the St. Peter sandstone in northwestern Indiana and northeastern Illinois. The contour interval is 200 feet. The Kentland quarry district is shown by a small black square. (After Logan, 1931, and Lamar, 1928.)

In summary, it is evident from the above discussion that a Middle Ordovician sequence, approximating 350–400 feet in thickness, is brought to the surface in the quarry district east of Kentland. If the identification of the various units is correct, the section includes rocks ranging in age from St. Peter to Galena inclusive.

STRUCTURAL CONDITIONS

Regional Structure.—This area of deformed Ordovician rocks lies on the southwest flank of the Cincinnati geanticline at the head of a wide syncline opening toward the south (see Fig. 6). Neither of Logan's[45] most recent structural maps of Indiana, one of which is based on the top of the Trenton and the other on the top of the St. Peter, shows any marked deflection in the vicinity of Kentland. Likewise, Lamar's[46] structural map of Illinois, based on the top of the St. Peter,

[45] *Ind. Dept. Conserv., Pub. No. 108* (1931), pp. 21, 22.

[46] *Op. cit.*, Plate III.

shows no unusual structural conditions in Illinois just across the line west of Kentland. It may be that the wells on which the contours were based in both states were so located as to be off the structure, which might be of regional extent, but it seems more likely that the deformed area is small.

Size of the Disturbed Area.—The known exposures and their altitude are shown in Figure 1. They all lie within an area less than one-half of a square mile in extent. Two miles west of the Means Quarry, at Kentland, the top of the "Trenton" (which includes everything between the top of the St. Peter and the base of the "Utica" black shales) is in its normal position 380 feet below sea level, or 1,060 feet below the surface. The nearest deep well to the south is at Oxford, in southern Benton County, a distance of some 20 miles. The record given by Logan[47] shows the top of the Trenton to be 537 feet below sea level (1,273 feet below surface). To the north along the northern boundary line of Newton County the top of the Trenton lies about 200 feet below sea level (846 feet below surface). Five and one-half miles southeast of Rensselaer and some 18 miles northeast of the quarry district, the Trenton was encountered at a depth of 928 feet, or 250 feet below sea level. Ten to 15 miles east of the quarries, in southern Jasper County, wells reach the Trenton at from 250–350 feet below sea level (950–1,050 feet below the surface).

From the data just given the Trenton, at short distances in all directions from the quarry district, appears to lie in its normal position on the southwest flank of the Cincinnati geanticline. This suggests that the disturbed area is small and of local extent rather than of regional extent.

Two miles northeast of the quarries in Section 18 limestone has been encountered at a depth of 50 feet, but the age of the rock is not known. Three and one-half miles east of the McCray Quarry, near Goodland, an impure slabby limestone of Mississippian age apparently, although reported by Kindle[48] as Niagaran, was once exposed in a shallow quarry now filled with dirt and rubbish. South and southeast of the quarries, within a distance of 1 to 4 miles, coal has

[47] *Ind. Dept. Conserv., Pub. No. 108* (1931), p. 41.

[48] E. M. Kindle, "The Stratigraphy and Paleontology of the Niagara of Northern Indiana," *Ind. Dept. Geol. and Nat. Res., 28th Ann. Rept.* (1904), pp. 413–14.

been reported in a number of borings within less than 100 feet below the surface, and extending downward for 100 feet or more.[49] To the southwest in Section 33, 103 feet of drift cover shale of probable New Albany (Devonian or Lower Mississippian) age. At and near Kentland (Sections 21 and 22) New Albany black shale is reported from 100 to 150 feet below the surface. The general elevation of the Kentland region is about 700 to 800 feet above sea level.

Here again the evidence suggests that the disturbed area is small, especially if the inlier formed by the upstanding mass represents most or all of it. The possibility remains, however, that part of the deformed rocks may have been covered by younger sediments. This of course presupposes that the disturbance antedated the deposition of the younger sediments.

Local Structure.—The local structural conditions are shown on Figures 1 and 4. In the McKee Quarry the beds dip east at an angle of from 58° to 71°, and the strike trends generally north-south. The top of the beds is to the east. In the Means Quarry the strata dip north at an angle of from 51° to 66° and strike in a general east-west direction. The top of the beds is to the north.

In the large McCray Quarry the structure is much more complex than in the two smaller quarries. In the northern half of the quarry the beds consistently trend in a general north-south direction and dip west at a high angle, with the top of the beds to the west. A definite sequence of beds has been repeated several times, apparently by faulting rather than by folding as pointed out in the earlier discussion. Several nearly vertical faults and zones of brecciation appear along the north wall, but the amount and direction of movement are usually not apparent. Along the eastern face of the quarry an almost vertical fault zone, dipping to the east, extends roughly parallel with the strike from the north wall south for some distance, and may be seen at several places along the east face of the quarry for several hundred feet to the south. Owing to the general fractured condition of the rocks, faults and brecciated zones are not readily distinguished. The fault responsible for the duplication of the beds along the north wall cannot be ascertained with certainty.

In the southern half of the quarry the beds do not show any uni-

[49] G. H. Ashley, *op. cit.*, pp. 184–91.

formity of dip and strike. The surface shows a fault mosaic of tilted blocks, some of which have been folded. In general the rock, which consists of limestone, sandstone, and shale, is highly fractured. Some of the fault surfaces are curved and simulate bedding planes. One very well-defined fault may be observed in the southwestern corner of the quarry. Some drag-folding was observed in a thin sandy bed in the southeast corner of the quarry. This bed is no longer visible because of removal by quarrying. Overturning was observed in several places, but not much past the vertical. As a rule the strata appear to be only steeply inclined.

Everywhere there is abundant evidence of violent deformation. The rocks have suffered a great deal of crushing, as is well illustrated by the sandstone which has developed fracture cleavage; "shatter cones" are present in all of the rocks in the three quarries, except the shale; bedding faults and faults cutting across the bedding are seen frequently; and brecciation may be observed in a great many places. Only a cursory examination is necessary to arrive at the conclusion that the rocks failed chiefly by fracturing; and the general absence of folding along with the very extensive fracturing might suggest that the deformation was rapid and perhaps near the surface.

Not only does the southern half of the McCray Quarry show the most intense deformation, but here also the greatest amount of uplift has occurred for the oldest formations exposed are found along the south wall of the quarry. The east dip of the beds in the McKee Quarry and the west dip of the strata along the east side of the McCray Quarry suggest an anticlinal fold trending in a north-south direction. The existence of such a structure, however, is not certain. It is thought that the various differences in strike have been brought about by the differential tilting of a number of fault blocks.

Amount of Uplift.—The most recent information available indicates that the "Trenton" limestones in the vicinity of Kentland have a thickness of approximately 450 feet.[50] In the Kentland well already referred to the Trenton was encountered at 1,060 feet below the surface. It is apparent from these figures (1,060 plus 450) that the rocks exposed at the surface in the three quarries east of Kentland have been uplifted vertically approximately 1,500 feet. The

[50] W. N. Logan, *Ind. Dept. Conserv., Pub. No. 108* (1931), p. 8.

thickness of the St. Peter sandstone is not considered in the above computations.

Data on Magnetic Intensity.[51]—"In an attempt to obtain more information on the extent of the structure found in the three quarries a partial survey of the surrounding area was made with a Hotchkiss

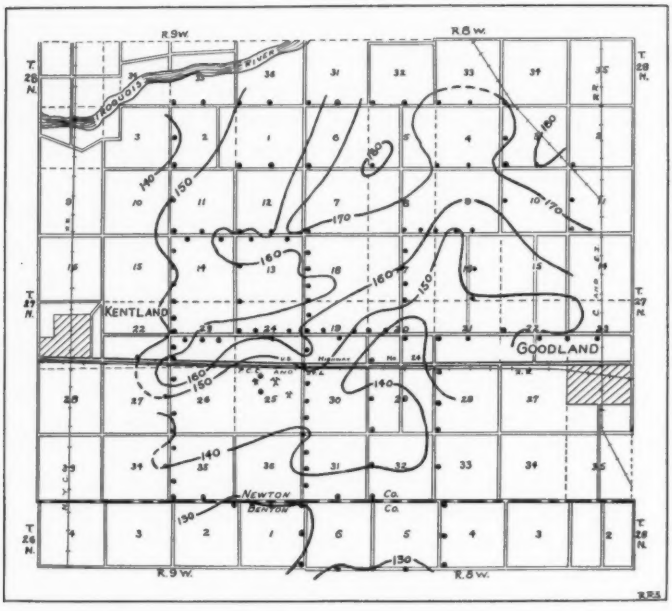


FIG. 7.—Map showing the variation in magnetic intensity in the vicinity of Kentland, Indiana. The isomagnetic lines are drawn 10° apart. Large dots show where readings were made. The survey was conducted by Dr. Justin Zinn, University of Wisconsin, on July 16 and 17, 1932.

superdip. The results of this survey are shown on the accompanying map, Figure 7. The instrument was one of the first models to be manufactured, but it proved to be quite satisfactory. The inclination of the earth's magnetic field at the quarry was determined to be 71° from the horizontal. The magnetic needle and the counterweight

[51] The following discussion was very kindly contributed by Dr. Justin Zinn, University of Wisconsin, who conducted the magnetic survey.

arm were then set 17° apart, thus using a sigma of 2° which made the superdip fairly sensitive. The counterweight was adjusted so that the position of rest of the magnetic needle was about at right angles to the magnetic field. In setting up the instrument to take a reading the azimuth was determined by orienting the instrument with the roads, since there was no compass to fit the base. The procedure introduced very little if any error, because the magnetic declination was negligible and the roads were all on section lines or quarter lines. The readings recorded were the maximum first down swing of the needle and as such are about twice the reading of the position of rest. They have not been corrected for diurnal variation, and temperature correction was made only on the readings which were taken in the early morning when the temperature was several degrees lower than during the rest of the day. Careful corrections in all cases would not alter the recorded readings more than 3 or 4 degrees, which change is insignificant as compared to the variations which were obtained.

"No detailed survey could be made because of insufficient time, and the readings were taken at intervals of ¼ or ½ mile. The results, therefore, show only the major trends of the magnetic lines, and not small details.

"It is interesting to note that the superdip survey shows a well-defined magnetic anomaly in the area in which the quarries are located. This anomaly is defined as a general area of greater intensity trending in an east-northeast direction. The quarries are located along the south side of it. Rather well-defined lines of intensity are apparent in the area, between which are lines of lower intensity. The latter trend northeastward, generally parallel to the magnetic area itself. Though the cause of the magnetic variation is not known, it seems fairly safe to assume that it is related to the underlying structure. The Paleozoic sediments of the region are not magnetic; therefore, the anomaly must be due to some body of rock beneath the sediments, perhaps a portion of the pre-Cambrian basement which has been brought nearer the surface, or perhaps some intrusive rock of a magnetic character. The lines of higher readings are places where the underlying magnetic rock is probably closest to the surface; therefore, these lines show anticlinal structures. The variations in

readings over the lines suggest, however, that the anticlinals are dome-like and not of great length. They may thus be the result of the intrusion of some rock beneath them rather than the consequence of a diastrophic movement."

Probable Type of Structure.—The first statement of consequence concerning the possible character of the structural complex at Kentland was that made by Ashley,[52] who suggested an upheaval due to "volcanic agencies." Ward[53] considered it to be a "synclinal much broken in the folding." Cumings[54] suggested "cryptovolcanic activity" as a possible origin. Chamberlin[55] referred to it as ". . . . a very sharp, narrow-crested anticlinal fold" and more recently by letter and discussion has favored the idea of "push-up" from below, most likely of the cryptovolcanic type. Bucher, in a very recent letter to the authors, considered the structure to be of cryptovolcanic origin similar to some five typical cryptovolcanic areas which he has studied.

Any theory of origin which will explain satisfactorily the structural complex present in the three quarries must consider the following facts:

1. Vertical uplift to the extent of approximately 1,500 feet has taken place.
2. Rocks ranging in age from basal St. Peter to Galena have been involved.
3. The rocks have failed under stress mainly by fracturing and faulting, and less commonly by folding.
4. Fracture phenomena such as brecciated zones parallel to and inclined to the bedding; "shatter cones"; fracture cleavage; and faulted drag folds occur at various places, in some cases abundantly.
5. The disturbed area, so far as can be ascertained at present, is not large, and apparently not regional in extent.
6. The disturbed area is located on the south side of a pronounced magnetic high, which is bounded by magnetic lows on the north, west, southeast, and south.

[52] *Ind. Dept. Geol. and Nat. Res., 23d Ann. Rept.* (1899), p. 190.

[53] *Ibid., 30th Ann. Rept.* (1906), p. 216.

[54] *Handbook of Indiana Geology*, Ind. Dept. Conserv., Pt. IV (1922), p. 449.

[55] *Amer. Jour. Sci.* (5), Vol. VI (1923), p. 217.

7. No evidence of hydrothermal alteration has ever been seen, and no anamorphic minerals have been found.
8. The three quarries are completely surrounded by glacial drift, hence at no place can the Ordovician formations be seen in contact with younger rocks.

Regional faulting does not seem to be a satisfactory explanation, for faulting of sufficient magnitude would certainly be reflected in the structure of the Trenton and St. Peter. Furthermore, regional folding and associated faulting seem inadequate, because of the fact that in all directions outward from the disturbed area the Trenton and St. Peter do not appear to have been deformed, and present knowledge indicates a local rather than regional disturbance.

It is the conclusion of the writers that the structural complex, comprising chiefly a mosaic of fault blocks, east of Kentland, was produced by forces acting vertically and originating at considerable depth. Whether the forces were exerted by the intrusion of a plug of deeply buried igneous material or by the uplifting of a block of the crystalline basement, which was outlined by pre-existing faults or joints, is unknown. It is believed that the deformation was rapid and violent and that the rocks which are exposed at the present time were deformed under a light rather than a heavy load, else the limestones would have recrystallized rather than fracturing so intensely. The origin may then be considered "cryptovolcanic," using that expression in the sense that it has been used by Bucher[56] in describing several similar areas in the Mississippi Valley region.

The time of deformation is vague. The youngest rocks involved are of Middle Ordovician age. The entire structure, with the exception of the three quarry openings, is covered with glacial drift. The disturbed rock cannot be seen in contact with either older or younger formations. Hence the only statement that can be made at the present time is that the deformation took place after the Middle Ordovician and before the Pleistocene glaciation.

[56] W. H. Bucher, "Geology of Jeptha Knob," *Ky. Geol. Surv.*, Ser. 6, Vol. XXI (1925), pp. 193–237; "Crypto-volcanic Structures of Europe and America," *Pan-Amer. Geol.*, Vol. XLIII (1925), pp. 148–49; "Wells Creek Basin, Tenn., A Typical Cryptovolcanic Structure," *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932), pp. 147–48. See also W. R. Jillson, "An Isothrustic Hypothesis," *Pan-Amer. Geol.*, Vol. XL (1923), pp. 251–58.

SUMMARY AND CONCLUSIONS

Three miles east of Kentland, Indiana, intensely disturbed strata of Middle Ordovician age (St. Peter–Galena) are exposed in three quarry openings. The exposures in this small area, not over one-half of a square mile in extent, reveal a sequence of sandstones, limestones, and shales of about 400 feet in thickness. Well data from surrounding wells indicate that these rocks have been uplifted vertically over 1,500 feet. A general stratigraphic column of about 400 feet in thickness has been erected by piecing together a number of fragmental sections. Three distinctive faunal zones were found. They represent fanuas of Stones River, Lowville ("Birdseye"), and Decorah age.

There appears to be a good sized area of very intensely deformed rocks, the oldest of the sequence, surrounded by less disturbed and less intensely fractured strata. The three quarries taken together present a mosaic of fault blocks. Strikes are quite variable and dips range from less than 25° to over 90°. Folding is rare. The disturbance is thought to have been brought about by cryptovolcanic activity, but the time at which it occurred is uncertain.

RELATIONS OF CHERTS TO STYLOLITES AT CARTHAGE, MISSOURI

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ABSTRACT

The cherts of the upper portion of the Boone formation at Carthage have developed largely, if not wholly, by replacement, with frequent preservation within them of fossils and bedding. Their distribution is controlled largely by bedding and not at all by joints or weathering surfaces. Many of them alternate with stylolites along bedding directions, were developed earlier than these particular stylolites, and have been impressed into the limestone above and below by solution of the latter concomitant with the growth of the associated stylolites. Some cherts of otherwise similar appearance show stylolitic borders and have developed after the stylolites by replacement up to the stylolitic partings. Two episodes of chert development are not inferred, but rather an overlap of chert and stylolite formation. Relations of these cherts to mineralization in near-by mines are briefly discussed.

During a brief stop at the limestone quarries at Carthage, Missouri, in the spring of 1932, the writer was impressed with the unusual opportunities there afforded for studying the formation of the cherts in relation to stylolite development. In the following September he spent several days at Carthage and vicinity in studying these relationships in the hope of obtaining useful data on the somewhat mooted question of the mechanism of chert formation and in the belief that such a study, conducted on the outskirts of the Tri-State area of lead and zinc mineralization where relationships were less complicated than in the heart of the district, might afford useful data bearing on the problems of mineralization. The results are presented here briefly and mainly in pictorial form. The courtesy of the management of the Carthage Marble Company in granting the freedom of their quarries is gratefully acknowledged.

Age of the limestones.—The limestone quarried at Carthage occurs in the upper part of the Boone formation, and collections of fossils made by R. C. Moore[1] have led him to classify these limestones as of Warsaw age. Separate collecting from different zones in the quarries was not found practicable.

[1] R. C. Moore, "Early Mississippian Formations in Missouri," *Missouri Bur. Mines and Geol.*, Vol. XXI (1928), p. 245.

Attitude of the beds.—The limestones are nearly flat-lying and essentially undisturbed but for the presence of a few nearly vertical joints, which have not appreciably displaced the beds, and the rare occurrence of zones of brecciation cutting steeply across the bedding. One of the brecciated zones in a large loose block was from 4 inches to 1 foot in width and traversed the limestone nearly at right angles to the bedding and the stylolites. Most of the fragments are of the normal limestone in a slightly darker limestone matrix, but some of the fragments are angular chert.

Composition of the limestones.—Tests with Lemberg's solution on numerous samples brought back to the laboratory check the available analyses in showing that the limestones are nearly pure calcium carbonate (but for the cherts).

Origin of stylolitic partings.—The origin of stylolitic partings in limestones has been ably studied in recent years by Stockdale[2] and need not here be considered in detail further than to say that they are now generally recognized as products of differential solution of two limestone beds starting usually along bedding-plane contacts, and proceeding under a load of overlying sediments without the development of appreciable open spaces. The relatively insoluble components of the limestone become concentrated along the sinuous division between the two limestone layers as a thin residuum which, as shown later, may become a barrier to subsequent development of chert.

Stylolites have not been described, so far as the writer is aware, from unconsolidated materials, and their presence implies therefore a considerable degree of consolidation of the rock prior to stylolitic development.

For the progressive growth of the stylolitic prongs, the solution of both of the limestone beds is essential. Stylolites would usually not be expected to *develop*, therefore, at contacts between limestone and chert because of the relatively small solubility of the latter. In the Carthage quarries they have not developed along such contacts. If, as would commonly be the case, the two limestone beds dissolve at different rates, the mean position of the parting between the two

[2] Paris B. Stockdale, "Stylolites: Their Nature and Origin," *Ind. Univ. Studies*, Vol. IX, Study No. 55 (1922), pp. 97.

beds will shift. Furthermore, under these circumstances the insoluble residue will be derived from a thickness of limestone greater than—perhaps much greater than—the length of the stylolitic prongs.

General relationships of the cherts.—In the Carthage quarries there is no development of cherts along joints, solution channels, or zones of brecciation. There is no evidence that they are more abundant near the capping of residual soil and its enclosed chert fragments

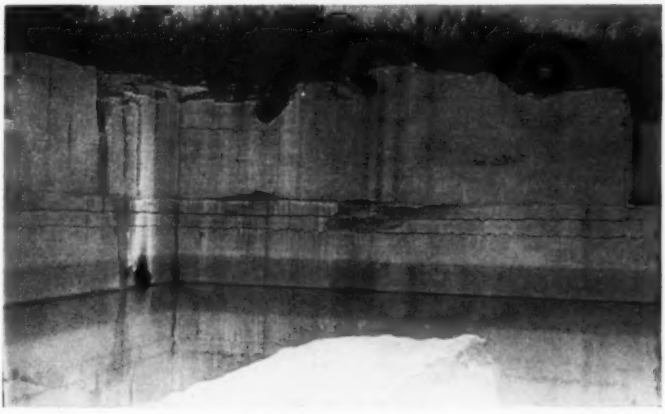

FIG. 1.—Stylolites shortly beneath residual soil capping the Carthage limestone. Note the absence of cherts near this erosion surface.

than at greater depths. Some of the limestone beneath the residual soil is nearly free from cherts (see Fig. 1). Their distribution is controlled largely by the bedding and they are much more abundant in certain beds than in others.

Although all the cherts are similar in general appearance, they show noteworthy contrasts in their modes of occurrence which carry implications as to genesis.

Cherts of rounded outlines distributed along bedding planes.—The vast majority of the cherts possess rounded outlines and smooth exterior contours but for certain minor striations later to be described. The maximum dimension of most of them lies in the bedding direction, but in some the dimensions inclined to the bedding

may equal or even exceed the horizontal dimensions. Their diameters parallel to the bedding may reach a yard or more, whereas their diameters perpendicular to the bedding range from a fraction of an inch to 2 feet.

Most, but not all, of the rounded cherts related to bedding planes are associated with stylolites, an association which signifies that certain bedding planes were favorable channels both for the solution processes responsible for the formation of stylolites and for those involved in the development of cherts (Figs. 2 and 3).

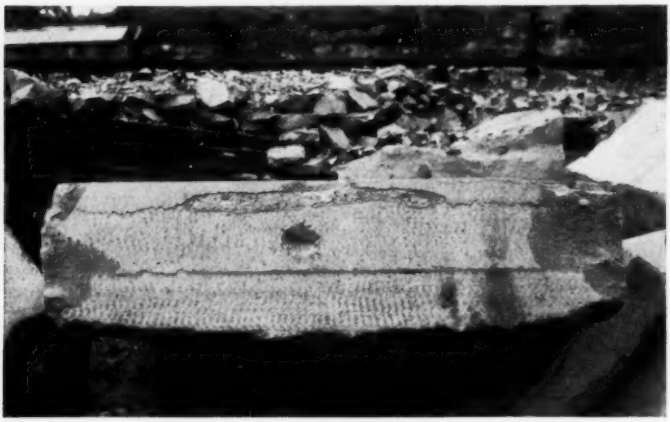

FIG. 2.—Typical association of rounded cherts with stylolites in Carthage limestone quarries. The black bar above the chert is 7 inches long.

Where the camera could not advantageously be used in recording the relations between cherts and stylolites, tracings were made from faces cut by the channeling machines by the use of an indelible pencil on transparent paraffined paper. Figures 4 and 5 are reduced from such tracings.

Where cherts are developed along a single stylolitic zone, the stylolites invariably end where the cherts begin, as is shown in Figures 2–5. Did the development of these cherts obliterate the stylolites, or were the stylolites developed later than the cherts? If the former were the case we should expect to find, in places, remnants of stylolitic prongs above or below the chert boundaries and we might

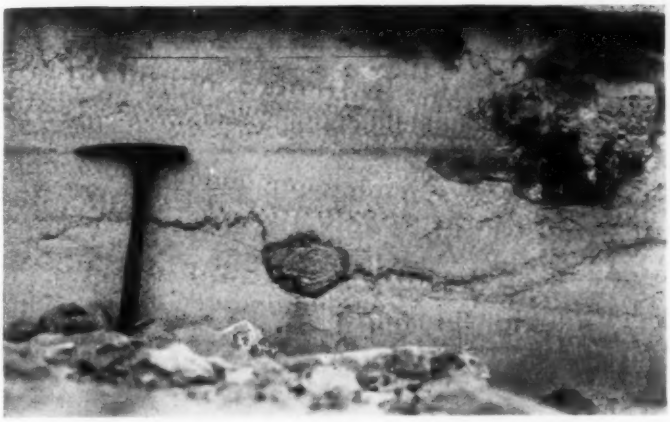

FIG. 3.—Chert nodule impressed into limestone concomitant with growth of associated stylolites. Carthage quarries.

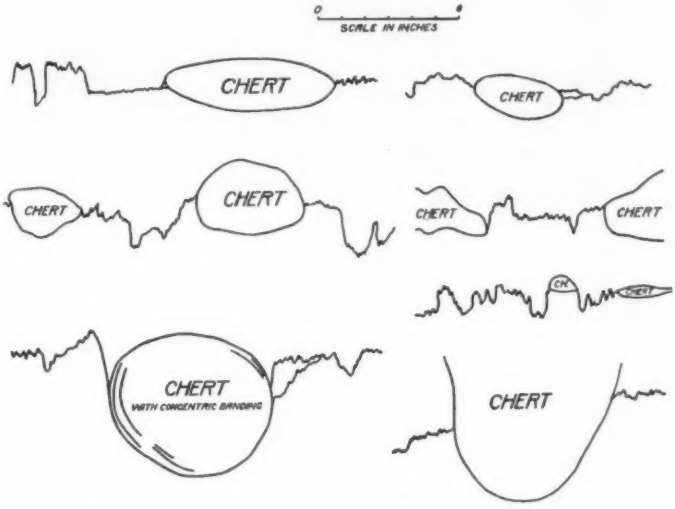

FIG. 4.—Reductions from tracings from quarry blocks or faces showing the commonest relation of cherts to stylolites. Carthage quarries.

also expect to find stylolitic partings traversing the cherts. As neither is present it is concluded that the cherts of this type developed before the particular stylolites with which they alternate, though not necessarily before other stylolites of these beds. In some places, as shown in Figure 5, the amplitude of the stylolitic prongs exceeds the widths of the associated cherts.

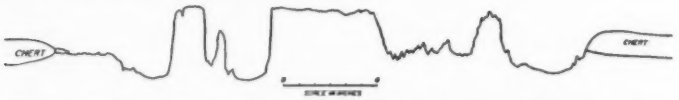

FIG. 5.—Reduction from tracing from quarry face showing stylolites exceeding n amplitude the width of associated cherts. Carthage quarries.

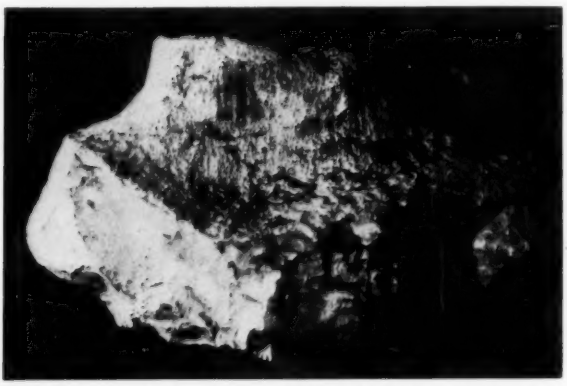

FIG. 6.—Striations on flanks of chert nubbin projecting into limestone. Developed during impressment of the chert into the bordering limestone. Carthage quarries. Natural size.

That the cherts of this type developed prior to at least much of the stylolitic growth is further evidenced by the surface grooving developed to some degree on the flanks of most of them. This grooving, though curving, in following the chert contours, trends in general nearly perpendicular to the bedding. Figure 6 shows its appearance on the sides of a chert nubbin which projected into the limestone. Some small cherts are ribbed in this way completely around their circumference. These striations are similar in appearance to those on the sides of the larger prongs of stylolites. They apparently indicate that the cherts have been pressed into the lime-

stone concurrent with the development of the adjacent stylolites. If this has occurred we should expect to find insoluble residues from the solution of limestone coating the tops and bottoms of the cherts, and this is the case where the associated stylolitic partings also carry appreciable residues.

Cherts showing stylolitic borders.—In contrast to the mode of chert occurrence described above, other cherts are bordered on one or on both sides by stylolitic partings clearly shown in Figure 7. To interpret these stylolites as developed after the formation of the chert by differential solution of chert and limestone would be at variance with the prevailingly smooth contacts of most of the cherts against limestone. The alternative explanation is that these cherts have developed after the stylolites that border them, the mechanism of their deposition being replacement, which halted at the layers of relatively insoluble residues that constitute the stylolitic parting. That this is the correct explanation is shown by the fact that in places the chert does not extend to the stylolitic parting but stops short of it, as shown in the center of Figure 7. In places, therefore, the stylolite is between chert and limestone and elsewhere between limestone and limestone, but there is no change in the amplitude of the stylolite in passing from one situation to the other.

It is obvious that replacement of limestone beds on both sides of a stylolitic parting may produce cherts traversed by stylolites. Such instances doubtless occur, but are rare and were not observed.

Cherts of irregular outlines.—Certain of the cherts of these quarries that are not associated with stylolites are of quite irregular—even of ragged—outlines as shown in Figure 8. These are less common, however, than the rounded cherts.

Replacement origin of the cherts.—Traces of fossils are commonly recognizable in the cherts in all the modes of occurrence that have been described, brachiopods and crinoid stems being the commonest types. In some, as in the specimen shown in Figure 9, certain fossils are still calcareous while others are siliceous. Bedding is preserved in many of the cherts as shown particularly in Figure 10 and less perfectly in Figure 9. In the specimen shown in Figure 10 the dark gray area in the lower lefthand portion is limestone whose bedding can be seen to parallel that in the chert. In the hand specimen the bedding can be traced continuously laterally from limestone into chert.

FIG. 7 (above).—Chert layer (shite) separated from limestone on both sides by stylolitic partings. Near the center of the picture a stylolite is for a short distance bounded on both sides by limestone (gray). Carthage quarries. Natural size.

FIG. 8.—Irregular development of chert (shite) in limestone. Carthage quarries. Natural size.

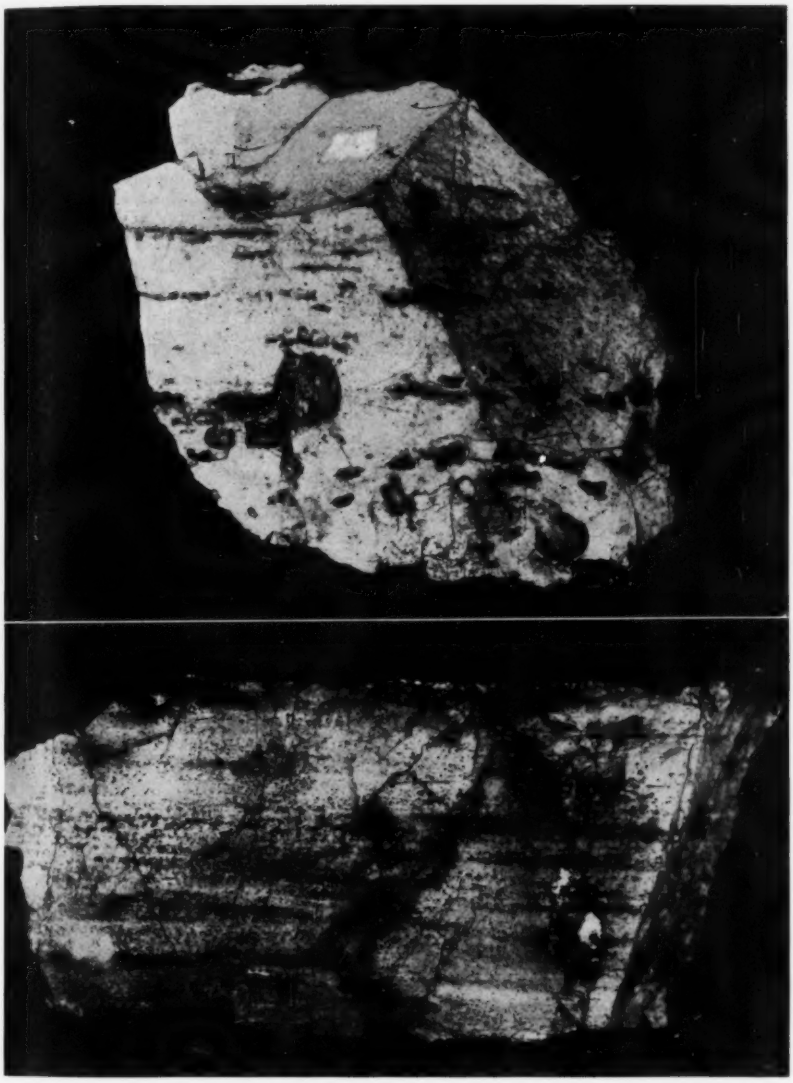

FIG. 9 (ABOVE).—Chert containing relics of bedding and both calcareous and silicified crinoid stems. Carthage quarries. Natural size.

FIG. 10.—Chert showing relics of bedding. The gray area in the lower corner is limestone whose bedding parallels that in the chert and is continuous with it laterally. Carthage quarries. Natural size.

Entirely aside from the general relations of cherts to stylolites, this preservation in the cherts of textures and structures characteristic of the limestone and the continuity of such features from chert to limestone constitute firm evidence of replacement origin.

Further progress of silicification may obliterate all traces of fossils and bedding and may develop concentric structures in some of the cherts as shown in one of the tracings of Figure 4.

Relation of chert development to mineralization.—Sulphides are practically absent from the Carthage limestone quarries although occasional minute grains of sphalerite have been found, as personally reported by C. F. Williams. Zinc mines, now long abandoned, occur, however, scattered along the north side of Spring River Valley from Carthage to Alba and the nearest of these is only 2 miles northwest of the Carthage quarries.

The writer was interested in comparing the relations seen on the dumps of some of these mines with those observed in the Carthage quarries. Essentially all the relations between cherts and stylolites described above were noted also on these mine dumps, and the cherts were similar in apparance. The striking contrast is in the presence of brecciation either associated or unassociated with sulphide mineralization. The breccias free from sulphides are composed of angular, light-colored chert fragments in a calcareous matrix which in some instances is a mixture of calcium carbonate with much dolomite, as shown by the Lemberg test. The chert fragments resemble in all particulars the cherts at Carthage. The matrix of some of these breccias upon long exposure has weathered to brown surfaces, and tests show the presence of small amounts of iron in both the ferric and ferrous state. Sulphides where present had developed mainly by the replacement of the calcareous matrix of such breccias, and all stages of transition from a purely calcareous matrix to a matrix wholly sphalerite can be seen. The writer saw no evidence for connecting the chert development at Carthage or in these neighboring mine dumps with the sulphide mineralization, although he specifically suspends final judgment upon this point. The younger generation of chert described as occurring so abundantly in the heart of the mineralized area as a component of the matrix of the breccias is certainly not conspicuous on these dumps and was not seen by the writer although it may be present.

SUMMARY AND CONCLUSIONS

The cherts of the Carthage limestone quarries, as shown by the preservation in them of fossils and of bedding and by the continuity of such bedding laterally with the bedding in the adjacent limestone, have developed largely, if not wholly, by the process of replacement.

Replacement by chert was conspicuously guided by bedding planes. There is no evidence that it was guided by joints or was more active near the present erosion surface than some distance below.

In some instances the replacement succeeded the development of stylolites and was abruptly halted at the relatively insoluble and impervious stylolitic partings. Such cherts were developed in consolidated limestone. In other instances cherts, mostly of rounded outlines, developed along bedding planes prior to the development of the associated stylolites which also follow the bedding in a general way. Such cherts, by the striations on their flanks, show evidence of having been impressed into the limestone above or below by solution of the latter concomitant with and keeping pace with the growth of the associated stylolites. These cherts, like those bounded by stylolites, carry fossils and relics of bedding and were developed by replacement. There is no specific evidence of the degree of consolidation of the limestone at the time that they formed, but there is no apparent reason for placing them in a different genetic category from the other cherts which they so closely resemble. The fact that some of the cherts are older than some stylolites and others are younger than other stylolites is not valid grounds for postulating two distinct episodes of chert formation inasmuch as the formation of both cherts and stylolites may have extended over a considerable period.

The relations at Carthage and the nearest zinc mines afford no evidence to connect the development of the light-colored cherts with the sulphide mineralization, although final judgment on this point must be reserved. The limestone breccias of the neighboring mines in contrast to the Carthage quarries do, however, show dolomitization and some development of iron in their matrix, and these changes were probably related to the sulphide mineralization. Sulphides are developed in these breccias mainly by the replacement of the calcareous matrix.

TEXTURAL AND LITHOLOGICAL VARIATIONS IN GLACIAL TILL[1]

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ABSTRACT

Till samples were collected from the Valparaiso moraine around the southern end of Lake Michigan, and along a line paralleling glacial movement from Chicago south. The samples were analyzed, and the pebbles classified according to lithology. In the Valparaiso moraine the mechanical composition was influenced by a loading of the ice with surficial material, and by drainage at the ice margin. The pebbles changed abruptly from dominantly limestone to shale and siltstone about 40 miles west of the corresponding bed rock contact. The westward movement of these pebbles was attributed to radial ice currents from the lake basin, over an area mantled with earlier drift. The samples in the line of glacial movement grouped themselves into three types on the basis of their mechanical composition. The results of the study are summarized in terms of the differentiation of tills by their textural composition. As an example of the method, the thickness of the Bloomington above earlier Wisconsin drift was determined in the absence of any intermediate weathered zone.

INTRODUCTION

The present paper has for its purpose an investigation of the textural and lithological variations in related samples of glacial till to determine the extent of variation in the line of glacial movement and at right angles to it. These variations are summarized in terms of the possible differentiation or correlation of such deposits. Two related areas were chosen in the eastern part of Illinois and in parts of Indiana and Michigan. A narrow strip in east-central Illinois was selected for the samples in the line of glacial movement, because it is crossed by ten moraines whose relative ages are clearly known. Further, bed rock differences occur along the traverse, and can be related to the textural and lithological variations in the till. The Valparaiso moraine was chosen for the study of lateral variation, both because it constitutes one of the moraines in the first traverse, and because it extends as a practically uninterrupted belt around the southern end of Lake Michigan. The bed rock underlying the Valparaiso moraine also undergoes a prominent change in western Indiana, and the effect of this change on the composition of the till may be considered.

[1] Published with the permission of the Chief, Illinois State Geological Survey.

The sampling areas are shown in their relation to the surrounding territory in Figure 1. Those parts of the moraines directly concerned with the study are shown in solid lines; adjacent field relations are merely indicated for purposes of orientation. It is clear that the Valparaiso moraine trends at right angles to the direction of movement of the ice sheet that deposited it. Similarly, the north-south line of sampling lies in the approximate line of glacial movement, as determined by Leverett and Taylor.[2]

In collecting the samples, road cuts or drill holes were used, and the samples were taken as far as possible, from zone 5 of the soil profile[3] or where this was not feasible, from zone 4 below the region of secondary lime concretions. Thus all of the samples are unleached, and most are unoxidized. In all cases the samples were taken from as near the surface as the development of the soil profile would permit, in order to avoid the possibility of unknowingly obtaining samples of older till. The field samples averaged from one to two kilograms each, and were preserved in No. 5 brown Kraft paper bags. To obtain the samples, the slump of the road cut was cleared off over an area of 1 or 2 square feet, and a composite sample was secured by detaching pickfuls over this area. Care was exercised to obtain all of a given fragment, to make certain that no pebbles or lumps of clay were lost. Sampling was done on the crests or distal slopes of the moraines, in order to have topographically comparable samples. Till-plain samples were usually taken from stream cuts or drainage ditches.

More than one sample was taken from most moraines in the traverse along the line of glacial movement, and a few samples were collected from intervening till plains. In deciding on the interval between samples along the Valparaiso moraine, preliminary studies were made on samples taken from a till ridge constituting one of its members. It was found over a length of 40 miles that samples taken at intervals of 1 or 2 miles showed only slight changes in composition from one sample to the next. The study indicated that intervals

[2] F. Leverett and F. B. Taylor, "The Pleistocene of Indiana and Michigan," *U.S. Geol. Surv. Mono. 53* (1915), Plate V, p. 62.

[3] M. M. Leighton and P. MacClintock, "Weathered Zones of the Drift-sheets of Illinois," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 28–53.

FIG. 1.—Map showing locations of samples

of 10 miles would not be too great if a considerable length of moraine was involved. In the present case the samples from the Valparaiso moraine average about 7 miles apart along a distance of 165 miles. In the laboratory the samples were crumbled into walnut-sized pieces and air dried. The dried pieces were then crushed with a rubber-tipped pestle until the fragments, excepting the larger pebbles, would pass through an 8 mm. sieve. The field sample was quartered with a Jones sample splitter until a laboratory sample of from 35 to 45 grams was obtained. The laboratory sample was analyzed by the pipette method in accordance with a technique recently described by the writer.[4]

VARIATION ALONG THE VALPARAISO MORAINE

Twenty-four samples of till from localities near the margin of the Valparaiso moraine were collected and analyzed. Figure 1 shows the sampling sites, and it will be noted that the samples extend around the lake from Elgin, Illinois, on the northwest, to Benton Harbor, Michigan, on the northeast. The samples were separated by intervals of from 4 to 10 miles, with an average interval of 7 miles. The average depth from which the samples were taken was 4 feet, and with few exceptions they were within zone 5 of the soil profile. They were collected from the distal half of the moraine, and most of them were secured within a mile of the distal edge.

The choice of the precise localities where samples were taken deserves some discussion. The till comprising the moraine was observed to undergo several striking changes as the moraine was followed along its extent. In its northwestern part, near Elgin, the moraine is composed almost entirely of a limestone gravel, and no exposures of clayey till were noted. Nevertheless, the moraine preserves its knob and kettle topography, and the material appears to be largely unbedded. South of the Fox River the till becomes more clayey in its appearance, and this condition persists without noticeable change until the Indiana state line is crossed. Near Valparaiso the moraine becomes quite sandy over large areas, with here and there a small area of typically clayey till. The sandy material is ap-

[4] W. C. Krumbein, "The Mechanical Analysis of Fine-Grained Sediments," *Jour. Sed. Petrology*, Vol. II (1932), pp. 140–49.

parently unbedded, and preserves the form of morainic swells and knobs, but it does not resemble typical till. East of Valparaiso the sandy nature of the material increases, and the morainic edge becomes more elusive, with wide flats extending for considerable distances into the moraine, giving the outer edge a peculiar finger-like pattern. Drainage ditches disclose that the flats are composed of gravel, and the morainic "fingers" that separate them are often quite sandy but structureless. Even here, however, small areas of clayey till were found. Farther east, beyond La Porte, the morainic edge becomes more distinct again, and the till assumes a more clayey character, although lenses of sand and gravel are not uncommon. In Michigan, southeast of Benton Harbor, the sandy and gravelly phases again predominate, but there also are found scattered areas of clayey till.

It appears from these considerations that the drainage conditions varied considerably along the extent of the moraine, and it may be expected that the mechanical composition of the tills was influenced by these factors. Under conditions of vigorous drainage the fine material is presumably washed from the till, and because of the variations noted, it was deemed advisable to confine the sampling, as far as possible, to areas of clayey till. By this means the effects of unusual drainage conditions would not color the conclusions advanced concerning a deposit assumed to have been laid directly by the ice.

Factors other than varying drainage conditions have influenced the composition of the till, and among these may be mentioned the underlying bed rock and the surficial material picked up by the advancing ice. Studies of the exposures between Valparaiso and La Porte disclosed that in some places the sand content of the till is so high that it appears to indicate the assimilation of dunes by the advancing ice. Further, sand dunes are quite common along the proximate edge of the moraine in this vicinity, but the distance to the present shore of Lake Michigan is too great to assume the migration of dunes from there. It appears more likely that after the melting back of the ice, the high sand content of the till favored wind action before vegetation gained a foothold. Leverett[5] noted the sandy

[5] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Surv. Mono. 38* (1899), pp. 356–57.

nature of the till in this locality, and he mentioned Taylor's suggestion that it was due to a loading of the ice with sand from dunes along the then shore of a pre-Valparaiso lake: a conclusion with which the present writer concurs. The bearing of the analytical data on this hypothesis will be touched upon later.

STATISTICAL TREATMENT OF THE DATA

The results of the mechanical analyses of the samples are shown in Table I. For convenience the north-south samples are included in the same table, but they will be discussed later. The data are arranged as percentages by weight in the several grades, and for ease of tabulation and plotting, the material larger than 1 mm. is combined in a single column. The data may be more readily visualized in graphic form, and Figure 2 shows the cumulative curves of the Valparaiso samples. It will be noted that the curves as a whole move across the chart fairly smoothly, and constitute a broad band, in which most of the members are approximately parallel, but several exceptions occur.

Six of the curves vary noticeably, in part at least, from the trends of the remaining curves. These are samples number 4, 15, 16, 22, 23, and 24, so numbered in Figure 2. Number 4 follows the main trend in the smaller ranges, and lags behind the others in the sand and gravel sizes, due to a larger proportion of coarse material. The general appearance of the till exposure from which the sample was taken was not different from that of the adjacent ones, but several large pebbles were noted in the sample analyzed. Inasmuch as the curve in the smaller ranges does not depart noticeably from the others, the variation is not due to the washing out of finer material, but probably represents a local loading of coarse material in the till. Numbers 15 and 16 were taken from the sandy part of the moraine in western Indiana, and the irregularities in these two samples are due to high percentages of sand. The smoothness of the curves in the finer ranges also is not materially upset, so that these as well show no washing out of the finer material, but a loading of the particular sand sizes instead. The sand ranges which are represented occur in dune sand, and this feature apparently corroborates the notion that surficial sand deposits contributed to the composition of the till here. Sample 22 is the lowermost curve in the smaller ranges, but rapidly

TABLE I

MECHANICAL ANALYSES OF ALL SAMPLES

SAMPLE	GRADE SIZES IN MILLIMETERS										
	Above 1 mm.	1 to 1/2	1/2 to 1/4	1/4 to 1/8	1/8 to 1/16	1/16 to 1/32	1/32 to 1/64	1/64 to 1/128	1/128 to 1/250	1/250 to 1/1000	Below 1/1000
1	10.0	2.6	3.9	4.8	4.7	9.9	11.9	13.3	10.2	12.9	15.8
2	9.3	2.0	2.9	3.5	3.1	8.9	10.5	12.3	11.0	17.9	18.6
3	8.6	2.8	3.7	3.7	3.0	6.5	9.0	10.7	11.3	19.6	21.4
4	19.0	1.7	2.7	3.6	4.2	8.8	8.7	9.9	9.0	13.7	18.7
5	4.2	1.4	1.8	2.3	2.4	4.7	10.8	16.5	14.9	20.7	20.3
6	4.6	1.9	2.3	2.7	3.1	6.3	13.0	15.7	12.0	19.9	18.5
7	4.8	1.1	3.8	3.3	1.9	7.9	10.5	13.7	12.9	18.9	21.2
8	5.3	3.2	4.1	4.3	3.3	10.5	14.0	18.2	11.7	11.4	14.0
9	4.2	2.0	2.5	2.9	3.3	10.2	11.9	13.5	12.4	16.0	21.1
10	5.4	1.2	1.5	2.4	2.9	8.4	9.6	14.9	11.0	18.7	24.0
11	3.0	1.4	2.0	3.4	3.3	5.4	9.2	13.0	11.5	23.4	24.4
12	3.2	2.1	3.7	4.0	2.3	8.1	13.9	11.5	11.0	17.1	23.1
13	5.0	1.8	2.8	3.8	3.5	8.8	13.8	16.8	12.6	13.6	17.5
14	4.1	1.7	3.2	5.2	5.6	12.2	11.5	12.4	10.5	15.0	18.6
15	4.1	1.9	10.0	11.2	5.7	13.9	11.7	10.1	5.9	10.4	15.0
16	4.1	2.2	7.6	9.5	7.2	13.3	9.8	10.5	8.9	9.4	17.5
17	2.6	1.3	3.8	4.9	3.7	8.1	12.5	12.7	10.7	16.1	23.6
18	1.6	1.6	5.7	6.6	3.4	6.9	7.8	11.5	11.7	19.4	23.8
19	1.9	1.1	2.0	3.6	3.6	8.0	10.3	13.7	13.2	20.4	22.2
20	2.6	1.7	3.8	4.9	3.9	8.3	14.0	14.9	13.0	14.4	18.5
21	6.6	1.7	3.5	6.0	6.2	11.7	9.6	11.7	10.6	14.6	17.8
22	4.8	2.1	4.9	8.4	7.8	19.4	16.0	11.5	7.3	8.7	9.1
23	2.3	1.9	9.0	12.2	5.4	9.5	8.2	9.3	7.5	17.7	17.0
24	2.7	2.5	10.5	15.9	7.2	6.1	5.9	4.3	8.1	16.7	20.1
A	13.9	6.9	15.5	15.1	9.3	7.9	11.0	6.7	3.6	4.3	5.7
B	10.2	6.2	14.7	14.9	9.9	10.0	8.8	7.3	4.6	6.4	7.0
C	8.6	4.7	11.8	14.5	9.2	8.5	12.2	7.2	5.5	7.8	10.0
D	6.3	4.1	12.8	14.6	12.0	9.6	13.8	7.7	5.2	5.7	8.0
E	10.2	5.0	11.1	11.8	8.3	8.3	11.0	8.2	6.4	8.9	10.8
F	9.8	4.4	9.1	9.3	6.3	6.9	11.2	11.5	9.4	10.0	12.2
G	19.7	4.5	9.9	9.6	7.1	10.3	9.8	8.9	5.9	6.7	7.3
H	13.0	4.1	10.0	10.8	8.3	7.8	10.9	10.4	9.5	5.9	9.3
I	9.5	5.5	13.2	12.4	7.0	6.0	11.3	8.1	7.5	7.1	12.2
J	4.7	2.8	5.0	4.8	3.4	7.6	11.2	15.2	12.2	16.3	16.8
K	5.8	3.2	4.5	4.9	3.8	8.8	10.2	17.6	14.4	13.0	13.0
L	7.9	3.1	5.6	5.0	3.7	7.3	9.5	16.9	11.1	16.1	13.8
M	5.8	2.0	2.9	3.2	3.4	5.8	10.1	21.1	12.1	18.5	15.3
N	7.9	4.3	5.9	5.3	3.7	9.6	8.2	17.2	14.6	10.5	12.8
O	3.7	2.1	3.0	3.2	2.8	5.1	7.6	20.2	16.9	17.4	18.0
P	2.1	1.2	1.7	2.0	1.8	2.9	7.7	14.7	16.5	22.9	26.6
P_1	4.0	1.0	1.1	1.6	1.3	3.9	6.0	11.2	12.3	23.4	24.1
Q	4.9	1.9	2.6	2.7	2.3	5.9	8.7	13.8	14.5	18.9	23.8
R	1.1	0.6	0.8	1.1	1.0	5.0	6.5	12.3	16.1	25.5	30.0
S	2.1	0.7	1.1	1.8	2.0	8.4	7.8	11.3	12.5	21.2	31.1
T	2.6	0.7	1.0	1.2	2.3	11.2	11.0	14.0	12.9	19.2	23.8
U	0.5	1.1	2.4	4.8	3.2	3.6	8.1	14.7	12.9	24.6	24.1
V	3.0	1.4	2.0	3.4	3.3	5.4	9.2	13.0	11.5	23.4	24.4
W	0.7	0.9	1.1	2.9	3.0	3.7	9.6	12.8	13.4	25.5	26.4

rises through the silt and finer sand sizes, to become one of the uppermost curves at the coarse end of the range. The low percentage of clay in this sample suggests that the finer material may in part have washed out due to drainage conditions at the time of deposition. Sample 23 is similar to 15 and 16, and from the field relations it appears that sand assimilation also occurred along the moraine southeast of Benton Harbor. Sample 24 departs most widely from the general trend of the curves. It has the average amount of clay,

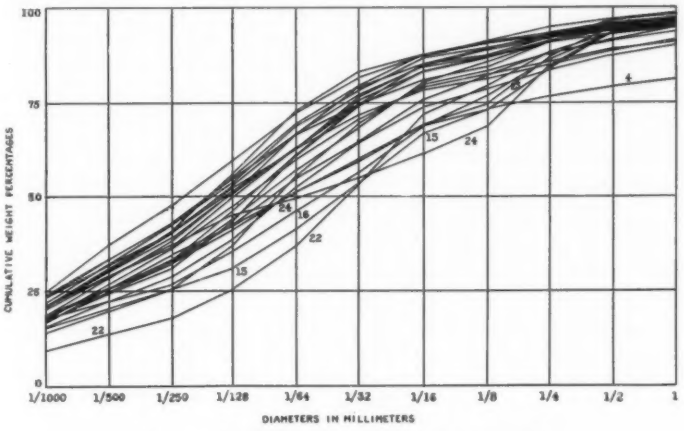

FIG. 2.—Cumulative curves of Valparaiso samples

but a striking decrease in the silt, and an increased amount of sand. The cause of this single variation is not known, and it would be hazardous to postulate a washing out of the silt without effecting a corresponding reduction of the clay. A noteworthy feature of the cumulative curves is that they show no systematic variation from one sample to the next, but appear to deviate within certain limits from a mean composition.

A qualitative comparison of cumulative curves may serve to bring out general relations, but it is desirable to have some means of comparing the samples more quantitatively. Such a device is available in the statistical treatment of the data, which furnishes a series of values for each sample. The nature of the frequency data imposes limitations on the significance of the statistical values obtained, and it is

important to recognize this point. It may be pointed out that the statistical values decrease in significance with an increase in the irregularity of the frequency curve. Tills have extremely irregular distributions, and the presence of several secondary maxima render them polymodal in aspect. Such polymodal curves may be due to several factors, but in tills they are probably due to a mixture of several distributions behaving under different laws, and contributed by the material picked up by the ice in its forward movement. Because of the composite nature of the data, a generalized method of statistical treatment has been used, so that the characteristics determined have at least the significance necessary to permit a comparison among the samples. The method used involves the median and the quartiles, which are read directly from the cumulative curve. The median represents the middle grain size, and the quartiles represent the grains one-fourth and three-fourths of the way along the range. The median may thus be used as an average grain size, and the quartile deviation as a measure of the scattering of the data. Trask[6] has discussed the application of median and quartiles to the analysis of sedimentary data, and has developed formulas for sorting and skewness. The writer has used the common equation $QD = \frac{Q_3 - Q_1}{2}$ for determining the quartile deviation of the samples in the present paper.

The medians, quartiles, and quartile deviations of all the samples studied are shown in Table II. It will be noted that the medians of the Valparaiso samples range in value from 0.0044 to 0.027. This represents the diameter in millimeters of the average grain size, and the range falls entirely within the silt sizes, whose limits are generally accepted as lying between 0.004 and 0.06 mm. diameter. Such a table of statistical values is not an end in itself when an entire suite of samples is considered. Various devices may be used to point out the significance of the data in physical terms, and among them the median procession curve is useful for indicating the variation in the average grain size as the samples are followed along the moraine. The medians are plotted as ordinates and the miles between succes-

[6] P. D. Trask, "Studies of Recent Marine Sediments conducted by the American Petroleum Institute," *Bull. 89, Nat. Research Council* (1932), pp. 60–67.

TABLE II

STATISTICAL CONSTANTS OF THE SAMPLES

Sample	Median	First Quartile	Third Quartile	Quartile Deviation
1	0.0135	0.0027	0.073	0.0351
2	.0090	.0017	.045	.0216
3	.0069	.0013	.045	.0218
4	.0142	.0019	.185	.0916
5	.0058	.0014	.018	.0083
6	.0075	.0016	.025	.0117
7	.0066	.0014	.027	.0128
8	.0130	.0037	.046	.0212
9	.0079	.0014	.012	.0153
10	.0061	.0011	.024	.0114
11	.0044	.0011	.019	.0089
12	.0072	.0012	.029	.0139
13	.0100	.0021	.033	.0154
14	.0110	.0019	.046	.0221
15	.0260	.0039	.140	.0680
16	.0200	.0031	.110	.0534
17	.0074	.0012	.030	.0144
18	.0060	.0011	.034	.0164
19	.0058	.0012	.023	.0109
20	.0093	.0019	.032	.0150
21	.0120	.0021	.060	.0289
22	.0270	.0075	.084	.0382
23	.0140	.0018	.130	.0641
24	.0170	.0015	.170	.0842
A	.1330	.0205	.420	.1998
B	.0940	.0150	.340	.1630
C	.0560	.0092	.252	.1214
D	.0620	.0131	.232	.1095
E	.0470	.0069	.280	.1366
F	.0235	.0048	.225	.1101
G	.0660	.0120	.480	.2340
H	.0440	.0079	.295	.1436
I	.0460	.0064	.295	.1433
J	.0100	.0021	.045	.0220
K	.0110	.0033	.052	.0244
L	.0112	.0026	.066	.0322
M	.0090	.0021	.013	.0127
N	.0125	.0042	.094	.0454
O	.0070	.0017	.020	.0092
P	.0041	.0009*	.012	.0055
P_1	.0027	.0006*	.011	.0052
Q	.0056	.0011	.022	.0105
R	.0030	.0008*	.009	.0043
S	.0034	.0006*	.015	.0070
T	.0056	.0010	.022	.0105
U	.0047	.0010	.014	.0065
V	.0044	.0011	.019	.0089
W	.0036	.0009*	.013	.0060

* By extrapolation.

sive samples as abscissae, as shown in Figure 3. The curve shows a certain rhythmic tendency, inasmuch as the medians of the samples vary between troughs and peaks in their course along the moraine. Several of the peaks may be identified as being due to special circumstances. Samples 4, 15, 16, 22, 23, and 24 are all higher than the average values. These samples were mentioned earlier as having erratic cumulative curves, and the high values of the medians are related to the shifting of the curves due to the loading factors mentioned. In addition, samples 1, 8, 14, and 21 are higher than the

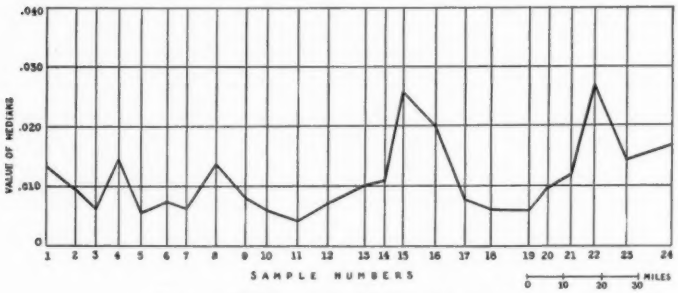

FIG. 3.—Median curve of Valparaiso samples

average value. Whether these latter high values represent some rhythmic fluctuations in the composition of the till, or whether they are fortuitous variations due to sampling errors, is a point on which it may not be safe to offer an opinion. The suggestion is strong, however, that drainage from the ice, concentrated at several points along the moraine, may have increased the general coarseness of the till by washing out varying amounts of the finer material. It is curious in this connection that the intervals between such successive high points should be of approximately equal length.

THE LITHOLOGIC COMPOSITION OF THE TILL

The areal geology maps of Illinois, Indiana, and Michigan show that the bed rock underlying the Valparaiso moraine undergoes a pronounced change a short distance west of Valparaiso. The western half of the moraine, in Illinois and in the western part of Indiana, is underlain by Silurian limestone and dolomite. Between Valparaiso

and a point southeast of Benton Harbor the bed rock is predominantly a black Devonian shale, and north of that point to beyond the edge of Figure 1, the bed rock is gray to blue Mississippian shale. West of the main contact between the Silurian and Devonian in western Indiana occur local areas of Devonian siltstone and shale, which appear to extend into the eastern part of Illinois.[7] Similarly, the bed rock in Indiana, while predominantly shale, is locally a Devonian(?) limestone, as at Michigan City, where a well penetrated limestone beneath the glacial drift.[8]

On the assumption that tills reflect the bed rock in the lithologic composition of their pebbles, it may be anticipated that a striking change in the pebbles should take place somewhere in western Indiana, so that to the west, limestone should predominate, whereas to the east shales and siltstones should constitute the major part of the pebbles. The percentage of limestone may be expected to increase in the vicinity of Michigan City also. To determine whether this condition exists, a sample of all pebbles larger than 2 mm. was washed from each sample of till, and classified into lithologic types. The samples ranged from 200 to 500 pebbles each, and the results were expressed as percentages. Several types of pebbles were noted in the samples, which were divided into the following groups:

a) *Limestone pebbles*, which included mainly gray to buff dolomitic limestone, but dark gray pebbles, and some rather soft yellowish pebbles were present. These pebbles were tested with warm hydrochloric acid.

b) *Shale and siltstone pebbles*, which ranged from fine-grained black shale to typical siltstones. The siltstones are mainly drab to buff, and are often silty shales, sometimes feebly calcareous. Some gray shale pebbles were also noted. It was not expedient to separate the siltstones from the shales, owing to the gradations present.

c) *Crystalline pebbles*, which included igneous and metamorphic rocks, as well as fragments of quartz, feldspar, and the like. These pebbles constitute the erratic portions of the pebbles.

d) *Miscellaneous pebbles*, including the cherts, the altered pebbles, and a few which could not be classified elsewhere.

The results of the pebble counts are shown in the first half of Table III. In Figure 4 the data are plotted: the types of pebbles by per-

[7] Unpublished data of the Illinois State Geological Survey.

[8] W. N. Logan, *Petroleum and Natural Gas in Indiana*, Indiana Division of Geology (1920), p. 164.

TABLE III

PERCENTAGES OF PEBBLES BY COUNT

Sample	Limestone	Siltstone and Shale	Crystallines	Miscellaneous
1	79.2	13.6	3.6	3.6
2	82.9	10.2	4.0	2.9
3	84.7	9.7	2.6	3.1
4	83.7	9.4	2.3	4.6
5	87.5	6.8	3.1	2.6
6	82.1	11.2	3.9	2.8
7	42.0	49.0	5.0	4.0
8	7.6	89.4	3.0	0.0
9	9.9	80.7	4.5	4.9
10	11.4	83.4	3.1	2.1
11	14.1	81.1	3.2	1.6
12	11.6	79.9	6.8	1.7
13	8.8	83.5	3.7	3.1
14	10.3	83.0	3.5	2.7
15	7.3	84.9	3.2	4.6
16	2.9	86.9	3.7	6.5
17	3.8	80.5	9.2	6.5
18	3.2	73.9	13.5	9.4
19	10.0	79.8	6.7	3.5
20	23.2	65.9	6.9	4.2
21	23.4	62.9	7.5	6.2
22	21.6	64.5	8.7	5.2
23	0.0	72.8	13.3	13.9
24	11.0	45.7	20.0	23.3
A	13.3	57.0	18.0	11.7
B	12.2	61.3	13.9	12.6
C	15.6	55.8	16.0	12.6
D	9.6	65.5	12.7	12.2
E	18.0	52.0	18.9	11.2
F	14.2	58.6	19.8	7.4
G	14.6	63.6	11.8	10.0
H	19.8	54.1	14.9	11.2
I	16.6	62.5	15.9	5.0
J	10.3	79.4	6.4	3.9
K	10.9	78.1	6.5	3.5
L	13.4	67.1	6.6	2.9
M	7.8	85.9	4.8	1.5
N	7.9	86.1	4.4	1.6
O	10.5	84.3	4.1	1.1
P	7.3	86.6	4.5	1.6
P_1	25.3	70.6	1.8	2.3
Q	15.2	79.6	2.5	2.7
R	41.8	61.5	5.1	0.0
S	36.7	57.6	1.3	4.4
T	9.0	87.4	2.0	1.6
U	22.9	65.2	6.8	5.1
V	14.1	81.1	3.2	1.6
W	17.1	76.8	3.7	2.4

centages as ordinates and miles between samples as abcissae. The miscellaneous group is not included in the graph. It is apparent at a glance that the limestone curve drops rather abruptly in its course along the moraine, and that the shale and siltstone curve rises equally as abruptly. The curve of the crystallines, on the other hand, shows no abrupt change in its trend.

When the curves are examined in detail, it is noted that the prominent drop in the limestone content, from 80 to 10 per cent, occurs

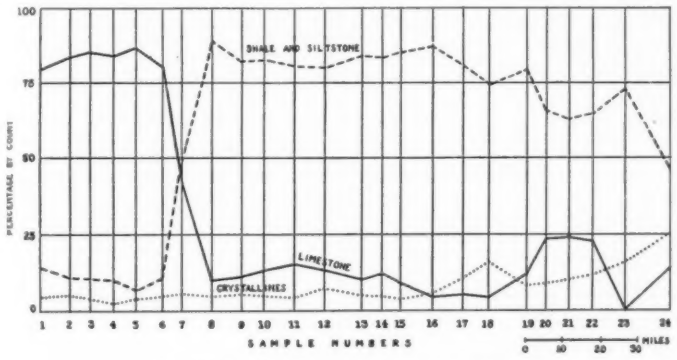

FIG. 4.—Lithology curves of Valparaiso samples

over a distance of about 13 miles, southeast of Joliet. In this same distance the shale and siltstone curve has its prominent rise. After following along at a low level for a number of miles, the limestone curve rises again, but drops almost to zero near the end of its course. The shale and siltstone curve, in the meanwhile, maintains its high level and only drops toward the end. The crystallines begin to increase in number near sample 16, and after some fluctuation, the curve swings up to 20 per cent of the pebble content.

The most striking feature in the diagram is that the point of intersection of the limestone and shale curves takes place not at the contact between the two types of bed rock, but about 40 miles west of it. This means that, although the bed rock is limestone under some 40 miles of the moraine, the predominant pebbles in the till are not limestone, but shale and siltstone. This condition appears to be due to

the relation between the sites of active erosion by the ice and the sites of deposition. That is, if the active erosion of bed rock was confined to the basin of Lake Michigan, and if the site of the moraine was covered by earlier drift, the westward currents of ice would carry shales and siltstones over the protected area to the west. Leverett[9] lists the depths to bed rock at several points along the moraine, and he expresses the opinion that some of the drift is undoubtedly of pre-Valparaiso age. His figures show that the total depth of the drift is from 100 to 300 feet, and of this he assigns about 65 feet to the Valparaiso. Thus a protective covering appears to have been present.

The contact between the Silurian and Devonian enters the southern edge of the lake near the Illinois–Indiana line, and hence lies in the western part of the basin. The presence of remnants of Devonian bed rock at Milwaukee suggests strongly that the contact continues in the western part of the basin throughout its extent in the area involved. Such a relation would clearly influence the westward transportation of shale and siltstone. Since the movement of the ice is radial from the central part of a lobe, the active erosion of shales in the western part of the basin would load the ice with pebbles of that composition, and they would still predominate in the drift-covered area above the limestone. The effect of this ice movement would be most strongly felt in the southwestern part of the lobe, because in those parts where the ice moved approximately due west the exposed limestone in the lake basin would effectively control the pebble content of the ice.

The change between a predominance of limestone and a predominance of shale and siltstone occurs over a zone only 13 miles wide. It appears from this that the width of the zone is largely a function of the distance traveled by the ice after the heavy loading of local material. In the present case the distance from the contact in the southern part of the lake basin to the edge of the moraine is only a matter of 40 to 50 miles. It is believed that the transition zone would have been appreciably wider if the moraine were farther from the contact.

The rise in the limestone curve farther east is undoubtedly related

[9] F. Leverett, *op. cit.*, pp. 353–55.

to the limestone bed rock which occurs beneath the drift at Michigan City. The rise in the crystalline curve near the northeastern end of the series is not readily explained. The relatively smooth increase in the curve argues against errors introduced by sampling. Since there are no known areas of crystalline rocks within several hundred miles of the area, there seems to be no simple explanation for the phenomenon.

In tying together the lithological and textural compositions of the till, it may be anticipated that a relatively resistant rock-like limestone would furnish large pebbles, while a softer shale would be ground down to silt and clay, and load the finer ranges. Curiously enough, no such situation was reflected in the samples. Attention is called again to the median procession curve (Fig. 3), in which the average sizes of the distributions were shown. It is interesting to note that in the same distance where the limestone decreases, the medians increase in value.

On the whole it seems that unconsolidated surficial materials in the path of the ice have a greater effect on the textural composition than indurated bed rock, even when the latter is a relatively soft shale. This seems to be borne out by the strong effect of the dune sand near Valparaiso, which appreciably shifted the median values of the curves, and distorted them beyond the usual limits of deviation. Next to the loading of surficial materials has been the effect of drainage along the ice margin. This effect has been secondary in the present study, because the samples were chosen to represent tills unaffected by varying drainage conditions, but it has not been possible to eliminate them entirely. Despite the attempted control of the drainage factor, it has appeared in the curves more strongly than the effects either of the underlying bed rock or of the lithological composition of the pebbles in the till. If perfectly random samples had been chosen, there is no doubt that the curves would have departed much more widely from the average composition.

VARIATION IN THE LINE OF GLACIAL MOVEMENT

Twenty-three samples of till arranged in the approximate line of glacial movement were collected and analyzed. Figure 1 shows the sampling sites, which extend from a point south of Chicago to be-

yond Paris. In order that the moraines traversed may be familiar to the reader, it should be pointed out that samples *A* and *B* were taken from the Shelbyville moraine, *C* and *D* from the Cerro Gordo moraine, *F*, *G*, and *H* from the Champaign moraine, *J*, *K*, and *L* from the outer Bloomington moraine, *M* and *N* from the Cropsey ridge (middle Bloomington of Leverett), *O* and *P* from the Chatsworth ridge (inner Bloomington of Leverett), *Q*, *R*, and *S* from the Marseilles moraine, *T* from the Rockdale moraine, *U* from the Manhattan moraine, *V* (which is identical with sample 11) from the outer

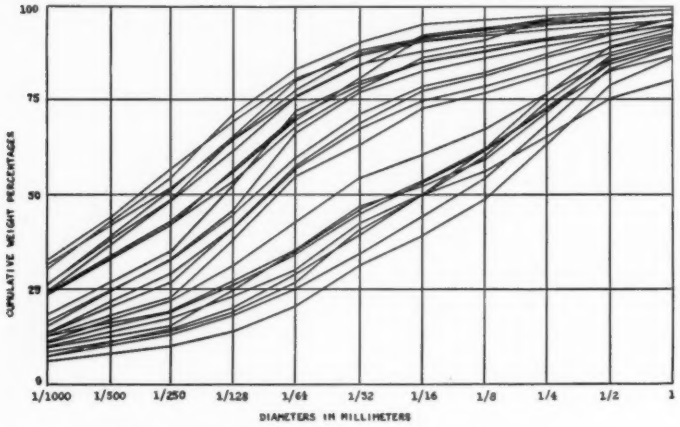

FIG. 5—Cumulative curves of north-south samples

Valparaiso moraine, and *W* from the inner Valparaiso or Tinley moraine.

In general, the samples were taken from parts of the moraine not directly associated with outwash channels in order to avoid complexities arising from drainage factors affecting the composition of the till.

STATISTICAL TREATMENT OF THE DATA

The results of the mechanical analyses of the samples are shown in Table I. Figure 5 illustrates the cumulative curves of the suite, and it may be seen that they divide themselves into three groups. The first group, represented by the nine lowermost curves, includes only

samples *A* to *I*. Of the upper fifteen curves, six depart from the general trend in the finer ranges, but merge with the others in the coarser grades. The six middlemost curves include only samples from *J* to *O*, and the uppermost curves are samples *P* to *W*. It may be seen from these curves that there is a strong suggestion of three types of till, and when the data are arranged in a triangle diagram, as in Figure 6, this cleavage into types stands out more clearly. The samples in the diagram are arranged according to their percentages of gravel and sand, silt, and clay, and it will be noted that samples *A* to *I* form the uppermost group, and that there is no overlap between this group and the other two. The samples below tend to arrange themselves into two groups, but there is some overlap present.

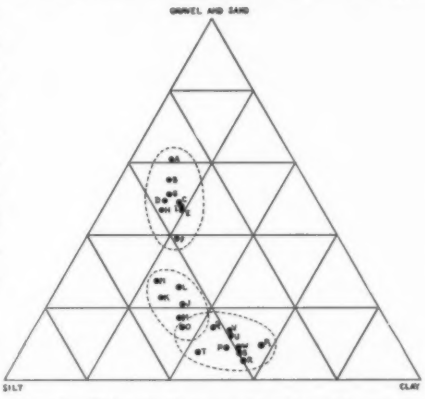

FIG. 6.—Triangle diagram of north-south samples

If the samples are considered in terms of moraines, it is seen that the uppermost group includes moraines of Shelbyville, Cerro Gordo, and Champaign ages. The central group has the outer Bloomington and the Cropsey ridges, and one sample from the Chatsworth ridge (*O*). Sample *P*, also from the Cropsey, falls in with the more northern moraines, which constitute the third group. Hence if three types of till are present, the boundary between the first and second is quite clear, but the data overlap with respect to the second and third. For convenience the three types of till will be referred to as the "Southern," "Middle," and "Northern," respectively.

When the statistical data of the samples, as shown in Table II, are considered, the break between the "Southern" and "Middle" types is clearly brought out. Figure 7 shows the median values of the samples as ordinates and miles between samples as abscissae. Inasmuch as more than one sample of some moraines are involved, the values

in such cases were averaged, and the number of samples in each average is indicated below the corresponding ordinate. The medians decrease rapidly along a curve from sample *A* to *I*, and over the very short interval between *I* and the next ordinate, there is a sharp drop to the Bloomington values. This marks the break between the "Southern" and "Middle" types. The extremely high values of *A* and *B* are difficult to explain, but it is possible that they show the effects of ice-margin drainage. Another minor drop occurs between

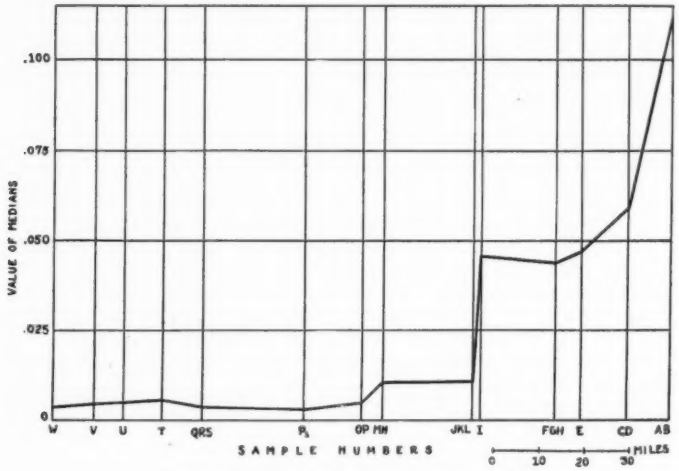

FIG. 7.—Median curve of north-south samples

the Cropsey and Chatsworth ridges, and from there north the values fluctuate but slightly. The position of the second break in the diagram indicates that the outer Bloomington and Cropsey ridges should constitute the "Middle" type, and that the Chatsworth and all moraines to the north should be classified as the "Northern" type.

THE LITHOLOGICAL COMPOSITION OF THE TILL

In order to supplement the data furnished by the mechanical analyses, pebbles were counted in a manner similar to that described in the case of the Valparaiso samples. The data are shown in Table III, and in Figure 8 the curves are plotted. In all three curves there

is a sharp break between the "Southern" and "Middle" samples. This substantiates the conclusion that the tills differ from each other. In attempting to relate the curves to the "Northern" type of till, it is found that the sharp break occurs not at the Chatsworth ridge, but in the till plain north of it. Since the contact between the Silurian limestone and dolomite and the Pennsylvanian bed rock occurs at a point south of Watseka, all samples from P_1 to W inclusive are underlain by the Silurian, and those farther south by Pennsylvanian

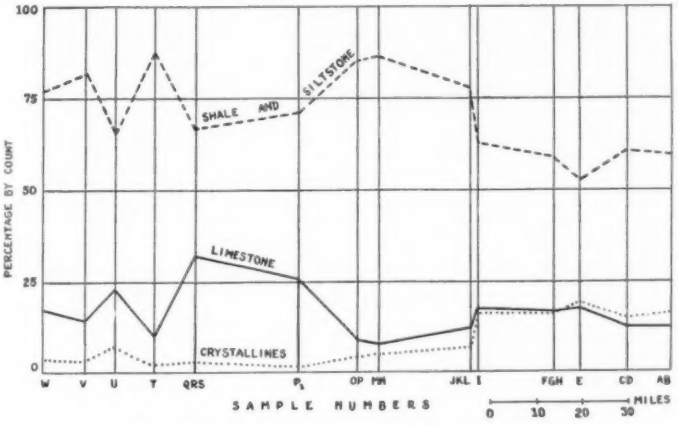

FIG. 8.—Lithology curves of north-south samples

strata. This situation seems to be reflected in the limestone curve, which shows an upward trend between samples O–P and P_1.

As further evidence of the cleavage into at least two types of till, a scatter diagram[10] was made, as shown in Figure 9. The medians of

[10] In preparing scatter diagrams, the samples are plotted as points, using the median as ordinate and the quartile deviation as abscissa. The centroid of each group of points is determined by taking the arithmetic average of the X- and Y-values of the points in each group. Next the mean absolute deviation of the samples from the appropriate centroid is computed by taking the sum of the absolute differences between the X-value of each point and the X-value of the centroid, and dividing by the number of points. The same procedure is followed with the Y-values. A rectangle, having sides equal to the mean deviation (or some multiple of it) is then constructed with the centroid as center. In Figure 9 the sides of the rectangles are equal to twice the mean deviations, to depict the smaller rectangle at an appreciable size.

the samples are shown as ordinates and the quartile deviations as abscissae. It will be noted that the samples in the "Southern" group are widely scattered, but the "Middle" and "Northern" groups comprise a more compact unit. There is no overlap between the "Southern" and "Middle" types, but the "Northern" merges to some extent with the "Middle," and for the purposes of the diagram they have been treated as a single group.

The centroids of the two groups of samples are shown by circles, and the deviation of the samples about these centroids is indicated

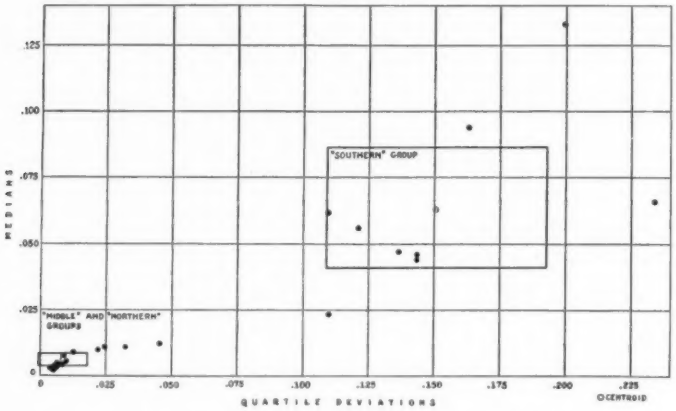

FIG. 9.—Scatter diagram of north-south samples

by the rectangles drawn with the centroids as centers. The "Southern" suite has the larger rectangle, and the samples of this group therefore depart more widely from the average composition of the set than do the other samples. Physically this concept relates to the homogeneity of the tills, since the degree of deviation from one sample to the next is a measure of how much alike they are in their composition. This relative homogeneity may be expressed quantitatively by comparing the areas of the rectangles, but as insufficient samples are involved in the present study to clothe the value with any statistical significance it is perhaps more appropriate to consider the rectangles as first approximations only.

In particular reference to the differences between the "Southern"

and the other types of till, it should be pointed out that the factors which controlled the loading of the Bloomington and later ice sheets with fine material are not clear from the samples themselves or from the field relations. The underlying bed rock can hardly be invoked, because the break in the mechanical composition occurs not at the contact between two different types of bed rock, but about 40 miles south of it in an area underlain mainly by shales and siltstones. The writer believes that the change in the textural composition must be traced to the movements of the ice after the Champaign till was deposited, and before the outer Bloomington moraine was laid. It is possible that the Champaign ice receded a considerable distance, and during its retreat locked in temporary lakes which served as sites for the deposition of silts and clays. When the ice advanced again, the inclusion of this material would profoundly affect the mechanical composition of the till.

There are numerous evidences in the Chicago area of temporary lakes formed in the wake of retreating ice sheets, and the material deposited in them would furnish sufficient silt and clay to load the ice. Whether the Champaign ice receded as far north as the Lake Michigan basin before it readvanced is not clear, but the conditions in that basin were ideally suited to the formation of such ice-locked lakes.

COMPARISON OF THE TWO SUITES OF SAMPLES

The data presented may suggest some of the differences between lateral variations along a moraine, and those that occur in the line of glacial movement. The medians of the Valparaiso till fluctuate in their absolute values, and the principal variations are due either to the assimilation of surficial materials near the ice margin, or to varying drainage conditions along the ice front. The medians of the samples in the line of glacial movement, on the other hand, reflect abrupt changes in the composition of the till as a whole. It thus seems that in the line of glacial movement the local variations do not appear to be as prominent as they are laterally along any one moraine, but the writer believes that if samples were taken from any considerable extent along each one of the moraines involved, the fluctuations of the medians would be of about the same order of magnitude as those of the Valparaiso till.

The influence of the immediately underlying bed rock on the mechanical composition appears to have been as inconsequential in one till as in the other. The pebbles in the tills along the line of glacial movement reflect the change from Silurian to Pennsylvanian more nearly at the contact than the Valparaiso till alone reflects the change from Silurian to Devonian. In general it may be said that the occurrence of pebbles of the immediately underlying bed rock in a given till is a function largely of protective coverings of the rock, and of the directions of the currents in the ice.

THE CORRELATION OF GLACIAL TILLS

Variations in the mechanical and lithological composition of tills have a bearing on the possible correlation of such deposits. The variations in the mechanical composition of the samples of any one set of till samples should be so small that the frequency-distribution graphs of the sets to be differentiated do not overlap. Such a condition exists in the case of the "Southern" and "Middle" tills along the line of glacial movement, but the "Middle" and "Northern" types overlap to some extent. Nevertheless, the overlap in the latter case, as shown by the triangle diagram and the median curves, did not include more than a single sample, although the sand and gravel contents were so closely related that certain differentiation may be doubtful.

The local variations shown by the samples of till from the Valparaiso moraine clearly indicate that it is not safe to base differentiation on a single sample. Even in the case of several samples, the field relations must be carefully investigated, because local surficial material and varying drainage conditions may greatly affect the composition of samples in a limited area. To test the effect of drainage conditions on the composition, a sample of Marseilles till was collected adjacent to a large outwash channel south of Kankakee. The composition was found to agree very closely with an average "Southern" type sample, and if differentiation had been based on such a random sample, an error of considerable magnitude would have been involved. It is necessary, therefore, that a sufficient number of samples be analyzed, to obtain the average composition of the till. By comparing *suites* of samples, the accidental variations due to drainage at the ice margin, or to the effects of local surficial mate-

rials, may be largely eliminated. The net effect will be the comparison of *sets* of data, and the differences among the sets, expressed as triangle diagrams, scatter diagrams, or the like, will form the basis of the differentiation. Once the cleavage into two types has been effected, it may fairly reasonably be predicted that a given sample of one or the other of the tills will fall within the category to which it belongs.

The pebble counts made in the present study did not reflect the changes among the tills as clearly as did the mechanical analyses. It is conceivable that the proportion of different rock types among the erratic pebbles may have shown some differences if investigated. Studies of the heavy minerals in some grade sizes were made, however, especially of the samples on both sides of the prominent break at Danville. The heavy minerals were separated from samples *I* and *J* by bromoform in the $\frac{1}{4}$–$\frac{1}{8}$ and $\frac{1}{8}$–$\frac{1}{16}$ mm. grades, and 1000 grains in each slide were counted. No outstanding differences were noted either in the two grades studied, or in the two samples. In both cases about 25 minerals were present. The predominant ones were hornblende, the iron ores, and garnet. The hornblende varied from 22 to 36 per cent, the ores from 20 to 31 per cent, and garnet from 10 to 13 per cent. Epidote, tourmaline, and hypersthene varied from less than 1 per cent up to several per cent, and all the others, among them actinolite, augite, muscovite, staurolite, rutile, titanite, zircon, and zoisite, were present from traces up to nearly 1 per cent. These counts were based on the acid-insoluble residues of the grades, so that neither calcite nor apatite were present.

Additional studies of the heavy minerals in other samples in the line of glacial movement were made, but in no case among the minerals was noted a variation greater than similar variations among other samples. The absence of any striking changes in the heavy minerals of these grades suggests that the "Southern" and "Middle tills are closely related, and this appears to strengthen the hypothesis that the "Middle" till resulted from the loading, in the manner suggested above, of the earlier till with silt and clay. Such additions to the finer ranges would not greatly affect the mineralogical composition of the sand sizes, but they would affect the mechanical composition of the till as a whole.

DETERMINATION OF THE THICKNESS OF THE BLOOMINGTON DRIFT

The sharp break in the mechanical composition of the two tills at Danville suggested the possibility of applying mechanical analysis to a typical differentiation problem. It seemed likely that beneath the Bloomington moraine there should be a considerable deposit of earlier Wisconsin drift, and it should be possible to determine the thickness of the Bloomington drift from a series of samples taken vertically. Samples were therefore collected along a new hard road on the west side of Lake Vermilion, northwest of Danville. Lake Vermilion is an artificial lake, dammed in the valley of the north fork of Vermilion River. Its altitude is approximately 575 feet, and its surface lies some 155 feet below the crest of the moraine in this general locality.

The sampling locality is immediately adjacent to the point from which sample *K* in Figure 1 was taken. The road crosses a small inlet of the lake, and rises to the north. Road cuts and small lake bluffs afforded an opportunity for collecting samples at vertical intervals of 5 feet through a total range of more than 60 feet. Twelve samples were collected within a distance of a quarter mile, only one by the use of a soil auger. The samples were numbered from the bottom up, the lake level sample being 0. Megascopic examination showed no striking changes among these samples.

Alternate samples were analyzed, to obtain some idea of the altitude of the break in composition. It was found that the change in composition occurred between samples 8 and 9, at 40 and 45 feet above the lake. To verify this, several lower samples were analyzed, and all of them showed the typical "Southern" composition. These are samples 2, 4, 5, 6, 7, and 8. Above the break, samples 9 and 11 were analyzed, and both showed the typical "Middle" composition. Figure 10 includes both the cumulative curves and a triangle diagram of the samples. In addition, sample *K* of the main set is included to indicate the composition of a sample from near the top of the moraine in this vicinity. It will be noted that the cumulative curves and the points in the triangle diagram separate into two groups between which there is no overlap. The dashed lines in the triangle diagram indicate the areas occupied by the till types in Figure 6.

The top of the pre-Bloomington drift has accordingly been placed

between 40 and 45 feet above Lake Vermilion. This is at an altitude of 615–620 feet, and since the Bloomington moraine rises to 730 feet, there are 110–115 feet of Bloomington drift present. The altitude of the Bloomington outwash plain in front of the moraine is from 640 to 650 feet. This altitude is from 20 to 40 feet above the contact of the tills, and if no erosion of the earlier Wisconsin drift by the Bloomington ice is assumed, the outwash of the Bloomington moraine ranges from 20 to 40 feet in thickness.

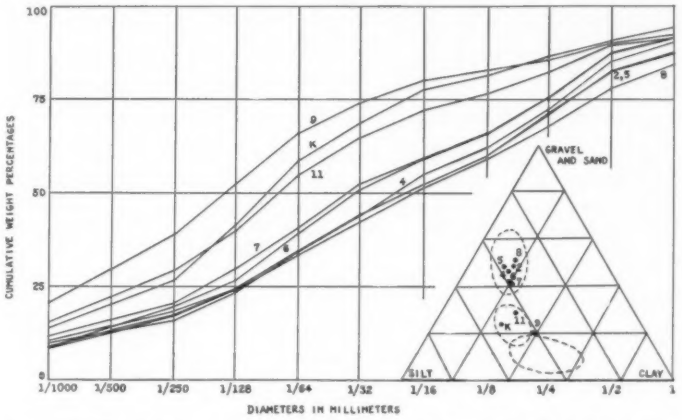

FIG. 10.—Cumulative curves and triangle diagram of samples for determining the thickness of the Bloomington drift.

SUMMARY

The present study has shown that till is perhaps not so heterogeneous as had heretofore been supposed, but that a given ice sheet tends to produce till having a fairly well-defined frequency distribution. This more or less homogeneous basic composition is modified locally by drainage conditions at the ice margin, and by the incorporation of unconsolidated deposits beneath the edge of the ice.

The ultimate source of the material comprising till is, of course, the terrane over which the ice moved, but the proportionate contributions made by the bed rock and by overridden surficial deposits are difficult to evaluate. The data from the Valparaiso moraine have clearly shown that the immediately underlying bed rock was not

necessarily related either to the pebbles in the till or to the mechanical composition. The clayey nature of the Valparaiso moraine is generally attributed to the Devonian shales in that region, and the presence of numerous Sporangites is an indication that some contribution has certainly been made. It is strange, however, that the mechanical composition does not reflect the change in the pebbles near Joliet, by being coarser to the west, where limestone pebbles predominate over shale and siltstone.

The present study has also shown that mechanical composition may be used as a means for differentiating tills under certain favorable conditions. Where these conditions prevail, as they do at Danville, differentiation is possible even in the absence of megascopically visible differences, or the presence of weathered zones.[11]

[11] The writer wishes to acknowledge the helpful suggestions and criticisms of Professors J H. Bretz, A. Johannsen, and F. J. Pettijohn of the Department of Geology of the University of Chicago. He is also indebted to Dr. M. M. Leighton, Chief of the Illinois State Geological Survey, who aided considerably in the development of the study.

ICE AGES AND THE DRIFT OF CONTINENTS

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ABSTRACT

The theory of the "drift of continents" as proposed by the late Dr. Wegener was supposed to account readily for the Pleistocene and the Permo-Carboniferous ice ages, and this was considered one of the most important proofs of its validity. In the following paper it is shown that his theory fails completely in this respect, and it is considered that the fixity of the continents is the more reasonable supposition.

To an orderly mind the arrangement of land and sea on our earth seems strangely capricious. If the earth was once a molten globe, as many authorities have assumed, it should have cooled to form a perfect spheroid with a uniform crust of sial overlying the sima and itself covered by an unbroken hydrosphere. There should be no land rising above the universal ocean. Through some blunder in the making of the world, however, the sial became bunched in certain areas, leaving the heavy sima uncovered over three quarters of the surface, where the waters gathered as oceans, the light continents rising as dry land.

Why this error occurred, is a profound mystery; but since it did occur, one may naturally ask: Why should not the sial have been arranged symmetrically, for instance, as an equatorial bulge, leaving the northern and southern ends of the earth covered by the sea; or as northern and southern continents with an equatorial sea?

Instead, we have the existing confusion of continents and islands sprawling over the surface, here and there assembled as compact areas, but more often tailing out as long peninsulas or loops of islands. There are hints of two or three patterns in the confusion, more or less jumbled together and suggesting a lack of consistency in the mind of the architect who had charge of the construction.

There has naturally been much speculation as to the causes and the history of the present helter-skelter arrangement of the land masses and oceans; and students of botany and zoölogy, as well as paleontologists and geologists, have taken a hand in redistributing

the lands and seas of past times to account for puzzling facts in their respective sciences.

The literature of biology and geology includes many suggestions of land bridges constructed across hundreds, or even thousands, of miles of deep sea to facilitate the migration of a *Glossopteris* flora or a group of primitive reptiles, or running birds or marsupials, or even shallow-water mollusks.

The machinery by which such stupendous building operations were accomplished has always been left vague; and of late years the geodesists, with their demonstration of more or less complete isostatic equilibrium in the earth's crust, have seriously shaken their foundations.

It is not surprising that the idea of a slow shifting of raftlike lands, meeting or separating, providing pathways for migration, or thrusting up chains of folded or faulted mountains at the edge of a continent, should be welcomed as providing a solution of hitherto troublesome problems; and when Taylor began the process with America and Wegener expanded it to cover all continents and all geological time, many geologists heaved a sigh of relief and looked with favor on the "drift of continents" as a way out of their difficulties.

There was good evidence of this during the centennial meeting of the British Association for the Advancement of Science in London the summer before last when "Problems of the Earth's Crust" were discussed. Several of the speakers referred to the theories of the late Dr. Wegener as solving the difficult problem of Permo-Carboniferous glaciation in regions which are now warm temperate or tropical.

It seems to me, however, that these theories have often been accepted uncritically and without a careful consideration of the supposed facts on which they are founded; and in the March number of the *Geographical Journal* a letter was published showing how inadequate Wegener's theories were to account for great periods of glaciation. As the *Geographical Journal* is not seen by many geologists, it has been suggested that the matter should be discussed in the *Journal of Geology;* and the following paper is an amplification of the points briefly mentioned in that letter.

There is no doubt that Wegener fully believed that his theories of shifting continents and wandering poles accounted satisfactorily for

the great times of glaciation, and his elaborate discussion of the late Paleozoic ice age makes it one of the important supports of his point of view. In *The Origin of Continents and Oceans* he says, "The riddle of the Permo-Carboniferous glacial period now finds an extremely impressive solution in the displacement theory. . . . . It is no longer a question of simplification which the displacement theory provides, it rather affords the final possibility of any explanation whatever."[1]

In regard to the Pleistocene he says, "However much one may have thought about the thorny question of the cause of the glacial period, it must in any case be admitted that the displacement theory does not make the comprehension of the phenomenon more difficult but more simple."[2]

Though Wegener takes up the Permo-Carboniferous ice age first, it will be wise to begin our consideration of the matter with the Pleistocene, of which we know most. In both ice ages Wegener solves the problem of refrigeration by bringing the glaciated regions close to the pole, so that they shall be within or near the polar circle. He does not suggest any general cooling of the earth.

In accounting for the Pleistocene ice age he crowds together Scandinavia, Greenland, Labrador, Newfoundland, and the British Isles to bring them within high northern latitudes, the north pole moving 20° from its present position to a point near the center of the mass; and he probably believed that this vast area was at least once covered by a single ice cap, since he referred to the outer terminal moraines of Europe and America as "joining up smoothly." He overlooks the fact that old marine beach lines are tilted landward on both sides of the Atlantic and not toward the central north pole of his map, showing that there were two ice sheets completely separated, each reaching the sea.

The climatic changes causing the Pleistocene glaciation were, however, not confined to special regions, such as Northern Europe and America or Patagonia in the south, but were world-wide. There was a fall of several degrees of temperature in the tropics as well as in temperate and polar regions, and the snowline was depressed 3,000 or 4,000 feet on high mountains everywhere. Ancient moraines are found at that distance below existing glaciers on the high Andes, on

[1] *Op. cit.*, p. 98. [2] *Ibid.*, p. 111.

the equatorial mountains of Central Africa, on one or two of the highest peaks in New Guinea, and on the Himalayas and other Asiatic ranges. A shift of land masses or of the poles could not have caused this universal lowering of the snowline on all the continents.

It should be noted also that the relative standing of the different climates was not affected by the world-wide refrigeration. The highly unfair arrangement of climates about the North Atlantic, by which England and Scandinavia have comfortable winter temperatures and harbors open all the year round, while Labrador has frigid conditions and the harbor of Quebec is closed four or five months in the winter, had its exact parallel in the ice age. The Baltic ice sheet reached south only to Latitude 50°, while the ice sheets of America pushed south to Latitude 38°, a difference of 12°.

Interglacial periods were not discussed by Wegener, but it is certain that the so-called "Ice Age" was not continuously cold, but was really characterized by rapid changes of climate, times when great ice sheets were formed alternating with mild intervals, one of them 4 or 5 degrees warmer than the present, as proved by its forest trees. It has been shown by Leverett[3] and others that there were four glaciations separated by interglacial times on both sides of the Atlantic and that the subdivisions of the Pleistocene found in the Alps, parts of Northern Europe, and England, correspond exactly to those of North America.

Are we to suppose that the countries huddled together to be near the pole in a glacial period were spread apart again for the interglacial time and then crowded together once more for the next glaciation, and that this contraction and expansion took place four times in the Pleistocene? The mere statement of the case shows how inadequate Wegener's theories are to account for the Pleistocene glaciation round the North Atlantic, where the most careful studies of the subject have been made.

If we go farther afield, we shall find that at least two glaciations, separated by a warmer interval, have been observed in many parts of the world. The two best-marked sets of moraines in the Rocky Mountains of Canada, the older one more extensive than the later

[3] "Comparison of North American and European Glacial Deposits," *Zeitschrift für Gletscherkunde*, Vol. IV (1910), pp. 242 ff.

one, have their equivalents on the higher peaks of the American Rockies almost as far as Mexico; and the same is true of the Andes in Equador, Bolivia, and Argentina, ending in Patagonia, where two glaciations and an interglacial period have been described.

If the whole 10,000 miles of the American Cordillera, including summits near the equator, show the same two glaciations, the older more severe than the younger, it is evident that no juggling of continents or displacing of poles can account for the facts. One can add to the American evidence the two glaciations on Mount Kosciusko, in Australia, the older one more extensive than the later, and the proofs of two or more glaciations in the Himalayas, to show that at least two refrigerations affected the whole world contemporaneously, implying causes operating everywhere.

One other point should be mentioned. Wegener helps out the crowding-together of the northern lands by a shift of the north pole 20° toward Western Europe, so as to bring all the northern glaciated areas into the proper latitude for arctic conditions; but that implies a corresponding shift of the south pole, which would place Patagonia in a warm temperate latitude; whereas it has just been shown that the Andes all the way to the southern end of the continent were twice glaciated simultaneously with the northern Rockies.

One of the most interesting problems of glacial geology is that of the source of the snowfall which nourishes an ice sheet. It has been shown by Peary and other explorers of Greenland, and more particularly by Professor Hobbs and his parties, that the ice sheet is normally the focus of an anticyclone and that the ordinary cyclonic storms do not sweep across the inland ice. Nevertheless, the snow that falls upon it must come ultimately from the sea by evaporation. In fact, there can be no doubt that a large amount of heat is necessary to produce a great ice sheet, since a million cubic miles of water must be evaporated from the sea and transported inland to condense as snow in the anticyclone just mentioned.

At a great distance from warm open seas ice does not accumulate, even with an intensely cold climate. Siberia had no important ice sheets in the Pleistocene, though beside the Arctic Ocean, since that body of water was too cold and too much ice-covered to provide the necessary evaporation. On the other hand, the European ice sheet

was close to the Atlantic and grew southwestward toward the Gulf Stream; while the two greatest American ice sheets, those of Keewatin and Labrador, covering 3,000,000 square miles at their maximum, pushed south into the Mississippi Valley to a latitude not more than 550 miles from the warm Gulf of Mexico. The southward growth of these greatest of Pleistocene ice sheets shows that even a glacial anticyclone must be fed by the evaporation from warm seas not too far away.

At present the greatest ice-covered area, that of Antarctica, appears to be in a state of starvation, because it is surrounded by cold seas largely covered with ice floes. A warming-up of the surrounding waters would probably greatly increase the snowfall and restore the ice sheet to the thickness it had at an earlier time.

If this reasoning is correct, the closing up of the North Atlantic (supposed by Wegener to be, along with the shift of the pole, the cause of the Pleistocene glaciation) would have the opposite effect, robbing the region of the nearby source of evaporation by which the ice sheets were nourished.

From the brief statements just made it is evident that the shifting of the lands and the migration of the poles, as worked out by Wegener, completely fail to account for salient features of the glaciation of the Pleistocene. Let us now turn to the more intense and more puzzling ice age which occurred toward the end of the Paleozoic, when the tropics were invaded by great ice sheets if the continents occupied their present positions.

Here it is the south pole about which Wegener grouped the glaciated regions, his maps showing South Africa, India, Australia and South America, along with Antarctica, crowded together, South Africa occupying the center, with the south pole wandering across it. In this way the regions where tillites have been found on a large scale are brought within a reasonable distance of the pole, not farther from it than some of the Pleistocene ice sheets were, from the north pole, e.g., in the Mississippi valley where, at their maximum, ice sheets reached Latitude 38°.

At first glance this seems to solve a most puzzling set of relations, for our present geography shows the Permo-Carboniferous glaciated regions as pushing up to the tropics in South Africa, and several degrees into the tropics in India, Australia, and South America, which

seems impossible. It is no wonder that some geologists and geographers have welcomed Wegener's explanation of the cause of glaciation.

A glance at Wegener's map, however, shows that this grouping of the continents would place the south pole and the area of glaciation in the heart of an enormous continent thousands of miles away from any source of evaporation to provide for snowfall. The supposed gigantic ice cap would lie in as arid and snowless a desert as that of Gobi in Central Asia.

But this is not the whole difficulty. Great as are the known areas of Permo-Carboniferous tillite, covering hundreds of thousands of square miles, there is good reason to believe that less than half the original area is known to us, the rest having been destroyed or buried under later rocks, or perhaps not sufficiently sought for.

It is well known that a continental ice sheet cannot move in one direction only, but must expand in all directions from its center, because its motion is due to the slope of its upper surface. This was true of the Pleistocene ice sheets; and in the case of the great Keewatin sheet, drift from the central parts was even transported hundreds of miles uphill and left thousands of feet above its source. The striae and the lines of the transportation of erratics radiate in all directions from the center.

Now it is a surprising feature of three of the Permo-Carboniferous tillite regions that the striations and lines of transport are in one direction only. This is strikingly true of the splendidly displayed Dwyka glaciation in South Africa, where all the evidence points to southward or southwestward motion. The southern margin of the Dwyka is heaped with massive drift deposits, while in the north we find the scoured surfaces and thin coat of till characteristic of a central area of glaciation, as recognized by the South African geologists. But where are the northward-pointing striae and the northern marginal deposits that must have existed when the great ice sheet finished its work? A few doubtful hints in Togoland and the Belgian Congo are all the evidence known of the northern half of the huge ice sheet that must have reached hundreds of miles in that direction.[4]

In the case of India it is the southern half that is lacking, and the same is true of Australia, where the ice moved only northward, com-

[4] A. P. Coleman, *Ice Ages Recent and Ancient*, pp. 132, etc.

ing, according to Süssmilch, from a vanished land of Tasmantis. These lost areas of glaciation, particularly that of Africa, would add immensely to the already unwieldy Gondwanaland and make it certain that some of the ice-covered areas would reach far beyond polar latitudes.

There is a still more serious difficulty opposing the Wegener arrangement of the Permo-Carboniferous continents in the fact, probably unknown to him, that in all of them the ice fields reached the sea, and in South America and Australia there was open sea on both sides of the continent. In the Australian deposits marine fossils occur in the matrix of the tillite, and there is good evidence that much of the ice edge was afloat, as now in the Ross Barrier of Antarctica. In the Indian glaciation the sea was reached at two points hundreds of miles apart.

From what has been said of the need for evaporation from warm seas not too far off, in the case of the great Pleistocene ice sheets, the facts just stated in regard to the Permo-Carboniferous arrangement of land and sea are perfectly natural; but they push widely apart the glaciated continents and make it certain that the ice-covered territory would reach latitudes that should have been warm, unless the whole world had undergone a cooling far more severe than that of the Pleistocene.

In the foregoing pages evidence has been brought forward to show that the known facts in regard to the two greatest periods of glaciation are not in accordance with Wegener's theory of drifting continents and shifting poles, although Wegener himself put stress on this side of his discussion as strongly supporting it. If one of its chief supports has failed when critically examined, doubts are raised as to his other lines of argument; and two points seem to me decidedly vulnerable. In his map of Gondwanaland the peninsula of India is shown beside South Africa in the neighborhood of the south pole. To reach its present position India must have traveled thousands of miles northward, crossing the equator, wherever that great circle may have been in the meantime. What forces can one assume as competent to drive a subcontinent across the bulge of the equator?

The continents may be considered as gigantic icebergs solidly frozen into an ice field many miles thick—the solid crust of basic rocks overlying the supposedly plastic sima. What force can one

imagine strong enough to start the iceberg moving, crashing through the cold and rigid sea bottom of basalt?

Not being a physicist, I may have overestimated these difficulties, which I hope some competent physical geologist will discuss; but unless far better evidence than any so far presented is brought forward in favor of the theory of the drift of continents and the shifting of the earth's axis, it seems to me that geologists should be decidedly cautious in regard to it. The usual evidence drawn from the scattered Archean areas of Greenland, the Arctic islands, and North America, suggesting a drifting apart from Europe, as used by Taylor and Wegener, provides a very unsafe foundation, since no one knows what underlies those narrow shallow seas. They may represent only superficial valleys carved in the Archean surface when it was dry land and now somewhat flooded by the sea. In the case of the Canadian arctic islands, this is almost certainly the case. No one has shown that they are fragments of sial separated by depressions filled with sima.

The other usual proof, accepted by a number of geologists and strongly supported by Du Toit, is that of the apparent fitting of South America into the Gulf of Guinea in Africa; but there is positive evidence, in the form of marine beds associated with the tillites, that the two continents were not in actual contact in Permo-Carboniferous times, but were separated by a sea of appreciable width, which greatly weakens the force of the argument.

Du Toit, in his detailed discussion of the early relations of South Africa and South America, admits the presence of a sea between the two continents at the end of the Paleozoic; but it is not intended to discuss the matter further, since Schuchert has given a powerful reply to Du Toit's line of argument.

The brilliant speculations of Daly, Joly, and Holmes, though of great interest to any thoughtful geologist, seem to the writer to be still only speculations, not yet well-established theories; and the old-fashioned belief that the continents were properly founded and stay where they were put still seems the most reasonable assumption.

The strange problems of brief times of glaciation, interrupting the usual mild climates of the world, are still unsolved; and this is specially true of the terrible visitation of ice in the tropics at the end of the Paleozoic.

A STUDY OF SOME DIABASE DIKES ON THE LABRADOR COAST

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ABSTRACT

In the course of geographic and geologic explorations centering about the vicinity of Nain, Labrador, observations were made on the abundance and field relations of the diabase dikes. A petrographic study of these with genetic conditions constantly in mind seemed to indicate that the percentage of olivine among the heavier constituents furnishes the most satisfactory index of the closeness of relationship between the various kinds of diabase found in this region. It seemed also that the monoclinic pyroxenes in them are much less aluminous than in ordinary augite. Both these observations may find wider application than to the Labrador material.

INTRODUCTION

Notwithstanding more or less justified objections to the term "diabase" it has been retained in this paper to designate igneous rocks with the mineral composition of members of the gabbro family but of medium-fine grain with more or less well-defined ophitic to intergranular texture. British petrographers may have agreed to abandon the term, but there seem to be a sufficient number of geologists who use it in a sense approximating the definition here given to justify its use, at least for the present.

Daly, in speaking of "trap dikes" in Labrador, says: "The continued prevalence of these intrusives along the coast for the 700 miles from the Straits of Belle Isle to Nachvak is, indeed, one of the most notable phenomena of its geology."[1] Practically the only trap dikes encountered in the section of the coast examined in detail by the writer, from Hopedale (Lat. 55°26′ N.) to Okak (Lat. 57°31′ N.) were diabases.

FIELD CHARACTERISTICS

Though diabase dikes are universally present in this section, their abundance is extremely variable, so that one may not encounter more than two or three in a distance of 20 miles, or half a dozen may occur within a distance of 100 yards.

[1] R. A. Daly, "The Geology of the Northeast Coast of Labrador," *Bull. Mus. of Comp. Zoöl.* (Harvard), Vol. XXXVIII (1902), p. 225.

They are apparently the youngest rocks in the region, since they cut every other rock of any considerable areal extent, while no other rocks were found cutting them. They are typical diabase dikes, generally between 2 and 50, and seldom exceeding 200 feet wide. A few of the larger dikes were traced along the strike for several miles, and careful work with favorable exposures would probably show them to extend much farther. Their dip generally approaches vertical. The strike of different dikes is very variable and shows no obvious correlation with any property of the dikes themselves or of their country rock. Though occasional intersecting dikes were noted, no difference in age of intrusion was determined.

They always show chilled margins with grain size increasing for some feet in from the contact until a normal maximum of about 0.75 mm. is reached. Irregular, coarse-grained, pegmatoid patches whose shape and distribution appear to be entirely without explanation and which grade into diabase of normal grain size are occasionally encountered. In these, plagioclase phenocrysts up to 3–4 cm. long are not uncommon.

Where dikes were small enough so that the structures in the country rock on each side could be correlated, no displacement of the wall rock was detected; hence the fractures into which the dikes have been intruded are probably not the result of faulting.

Occasionally a large diabase terminates sharply in a shear zone. This is apparently the result of faulting subsequent to its intrusion. At least some movement in the zone of fracture has occurred after consolidation. This is shown by occasional slickensided surfaces in the dikes, minor displacement of dikes along transverse fractures, and perhaps also fracture cleavage within a few dikes.

In most cases the topographic expression of the dikes seems to be primarily the result of glacial erosion. This was facilitated in the smaller dikes by comparatively abundant cooling joints, so that they form negative topographic features. The largest dikes, which have fewer joints, may form positive units, except possibly in the resistant anorthositic rocks about Nain. Wave action during post glacial times has been a factor in modifying the effects of glaciation by the erosion of deep fissures along some of the smaller dikes where they run normal to exposed sections of coast line. These fissures may ex-

tend some distance back from the coast, owing to elevation of the land since glaciation.

MINERALOGIC CLASSIFICATION OF THE DIABASES

Microscopic examination of thin-sections from thirty-five diabases in the Hopedale-Okak section shows that there is a rather wide range in mineralogic composition of these rocks. The nature and extent of the variations, as determined by the Rosival method,

FIG. 1.—Small valley probably produced by glacial erosion of a diabase dike. Kairtorsoak, northwest of Nain. Section several miles long.

are shown in Table I. The rocks form a linear series with almost perfect gradation between the extremes in which there is an equivalent of the great majority of all common rocks of the diabase group which have been described. In fact, it is remarkable how completely representative of the group as a whole this material is, when the limited number of specimens and the small size of the area from which they were collected is considered.

In the absence of a complete set of chemical analyses a classification of the diabases was developed which is based on their quantitative mineral composition. This classification is shown in Table II. The divisions depend essentially on the proportion of olivine in the mafic minerals. However, there are other, less well-defined, con-

TABLE I

DIABASE MINERAL COMPOSITION BY PERCENTAGE WEIGHT

Mineral	1	2	3	4	5	6	7	8
Plagioclase	51.9	61.	62.	59.5	57.	40.	56.	73.
Olivine	35.0	25.	11.	6.5	†	.....	.....	.....
Monoclinic pyroxene	4.0	7.	14.	13.5	20.	45.	27.	12.
Black iron ore	5.1	2.	7.	14.5	6.	6.	6.	4.
Apatite	0.6	1.	P	3.0	P	P	P	1.
Alkaline feldspar	A	P	1.	P	P	P	P	4.
Quartz	A	A	A	A	P	P	2.	
Biotite	0.3	P	P	P	P	P	2.	P
Talcose material	.....	.....	.....	.....	2.	.....	.....	.....
Chloritic material	P	P	P	P	P	P	P	P
Serpentinous material	3.1	P	P	P	P	?	?	?
Hornblende	.....	.....	.....	.....	12.	6.	6.	5.
Saussuritic material	P	P	P	P	P	P	P	P
Scapolite	?	P	.....	P	.....	P	P	P
Epidote group	.....	.....	.....	.....	.....	?	.....	P
Calcite	P	.....	P	P	.....	.....	P	.....
Yellow sulfide	.....	P	.....	.....	P	.....	P	P
Sphene	.....	.....	.....	.....	.....	.....	.....	P
Total*	100.0	96.	95.	97.0	97.	97.	99.	99.

* The difference between the total and 100 per cent gives an approximation of the amount of minerals indicated as present which is coarse enough to be readily given independent treatment in the grain counts. The finer-grained material is included with the mineral in which it occurs, and from which it is usually derived by alteration.

† Probably the mineral was originally present but has been entirely altered.

? Possibly present, but not detected with certainty.

A Careful study of the thin-section fails to show any of the mineral to be present.

P Present but in such small quantities or so fine grained and irregularly distributed that satisfactory determinations could not be made.

LIST OF SPECIMENS GIVEN IN TABLE I

1. Specimen 2–68, from near the center of a 15-foot porphyritic troctolitic diabase (Type IV) dike on Tumiktalik Island, which lies in the northeast part of the entrance to the big bay just south of Hopedale, called Deep Inlet on the chart (20).

2. Specimen 2–187, from near the center of a 100-foot olivine diabase (Type III) dike on the south side of Nain Harbor.

3. Specimen 2–87, an olivine diabase (Type III) dike, just below the lowest overfall in the rapids near the mouth of the Adlatok River, southwest of Hopedale in approximately Lat. 55°15′ N. and Long. 60°30′ W.

4. Average of Specimens 2–2508 and 2–2509, from the interior of a 65-foot porphyritic olivine diabase (Type III) dike on West Turnavik Island.

5. Specimen 2–94, from a point 20 feet from the margin of a 200-foot diabase (Type II) dike several miles inland from Black Head. The dike passes through Black Head, which lies on the coast several miles north of Hopedale.

6. Specimen 2–93, from the center of a 20-foot diabase (Type I) dike perhaps half a mile south of the point where Specimen 2–94 was taken.

7. Specimen 2–397, from near the margin of a 100-foot porphyritic diabase (Type I) dike on the east shore of Perkalujak Bay, 3 miles northwest of Nain.

8. Specimen 2–172, from near the center of a 100-foot sempatic diabase (Type I) dike passing 50 yards west of the summit of the hill immediately north of Nain.

comitant mineralogic variations which aid in determining the position in the series to which a given rock should be assigned. Chief among these is the optical character of the pyroxene. The develop-

TABLE II

MINERALOGIC CHARACTERISTICS OF DIABASE TYPES

Percentage		Type I	Type II	Type III	Type IV
Percentage of olivine in mafics		Absent	0–10	10–90	90–100
Plagioclase		Acid labradorite to oligoclase and maybe albite	Acid labradorite to oligoclase	Acid labradorite to andesine	Labradorite
Pyroxene	2V	Very variable	Variable	Generally moderate	Generally moderate
	Color	Faint brown or absent	Faint brown or absent	Moderate to strong reddish brown	Moderate reddish brown
	Dispersion	Weak	Weak	Strong	Strong
	Twinning	Generally present	Generally present	Absent	Absent
	Alteration to hornblende	Common	Present	Rare	Absent
Alkaline feldspar		Always present	Always present	Generally poorly developed	Absent
Quartz		Always present	May occur	Generally absent	Absent
Autometamorphism		Well developed	Well developed	Moderate to strong	Slight
Existing name		Konga-diabase	Kinne-diabase	Åsby-diabase	Åsby-diabase?

ment of interstitial quartz and alkaline feldspar and the amount and character of alteration products also seem to depend, at least to some extent, on the olivine ratio.

Olivine has failed to crystallize in the chilled marginal portions of diabase dikes in the region under consideration, even when the percentage of olivine is high in the interior of the dike. This fact might

be urged as an objection to a classification of diabases based on their olivine content. However, the few thin-sections of such chilled material studied suggests that there is sufficient difference between the chilled portions of several of the types of diabase, so that a fairly reliable estimate can be made as to the type that would have developed if chilling had not intervened. (If further study should prove this to be the case for all types, such material could be classed as a chilled phase of the type. Thus the mineralogic classification would not only become simplified, but would more nearly approach a chemical classification by the removal of an incidental physical factor influencing the mode of crystallization of the magma.

Certain other characteristics of diabases which are mentioned in the literature might be used for further subdivision of the group. These include the development of rhombic pyroxene, and possibly augite; unusual amounts of biotite, or quartz and alkaline feldspar; granular texture of pyroxene; large accumulations of plagioclase phenocrysts; and very coarse pegmatoid development. Only the last two features were occassionally noted in the Labrador material. Some of them are of such relatively rare occurrence that they probably represent very peculiar conditions and would therefore require a special place in any but a superficial system of classification.)

No place has been left in this system for augite, because no pyroxene was found in the rocks examined which could be identified with certainty as that mineral. The monoclinic pyroxenes of the olivine-bearing diabases have the reddish-brown color and inclined dispersion characteristic of titaniferous augite. However, spectrograms of the mineral show aluminum lines which are no more intense than those of typical green diopside from metamorphic limestone, and far less intense than those of several black hornblendes examined for purposes of comparison. Thus the mineral would not appear to contain sufficient alumina to call it "augite," despite the characteristic color and dispersion, unless it is a ferric iron variety.

TYPE IV DIABASE

Type IV diabase is similar to Törnebohm's Åsby-diabase[2] if his "augite" is the same as the monoclinic pyroxene of the Labrador ma-

[2] A. E. Törnebohm, "Ueber die wichtigeren Diabas- und Gabbro-Gesteine Schwedens," *Neues Jahrb.*, 1877, pp. 268–69.

terial, though it differs by the low percentage of pyroxene in the mafic minerals.

Specimen 2–68 has been taken as the representative of this type in the absence of a better specimen. Judging by the thin-section examined, the mineral composition of which is shown by No. 1 in

TABLE III

CHEMICAL ANALYSIS OF DIABASE SPECIMEN 2–68 WITH NORM

(Analyzed by Mary G. Keyes)

CHEMICAL ANALYSIS

Oxide	Percentage Weight	Oxide	Percentage Weight
SiO_2	43.31	TiO_2	1.92
Al_2O_3	13.32	ZrO_2	slight trace
Fe_2O_3	1.00	P_2O_5	0.03
FeO	11.07	S	trace
MgO	18.12	Cr_2O_3	none
CaO	8.30	MnO	0.10
Na_2O	1.63	BaO	none
K_2O	0.24		
H_2O	1.31	Total	100.52
H_2O	0.17		

NORM*

	Percentage Weight	Oxide	Percentage Weight
Or	1.67	Di	10.47
Ab	12.05	Ol	40.85
An	28.08	Mt	1.39
Ne	0.85	Il	3.65
Total	42.65	Total	56.36

Sp. G.: 3.03

C.I.P.W. classification: III.5.4.4., 1.4.1.2.

* Independent calculation of the norm by Dr. H. S. Washington yields identical results.

Table I, it would belong to this class without question. However, a thin-section from the same material examined by Dr. H. S. Washington has a composition which agrees much more closely with the norm calculated from a chemical analysis of the specimen, given in Table III. This discrepancy may best be explained on the assump-

tion that the composition of the rock is variable over short distances. The microscopic characteristics of the rock differ sufficiently from those of Type III diabase, with which it would have to be classified on the basis of the norm and Washington's thin-section, so that it seems best to classify it on the basis of the writer's thin-section. Another solution of the difficulty would be to raise the limiting percentage of pyroxene in the mafic constituents from 10 per cent to 20 per cent, so as to include both thin-sections.

The plagioclase of this type of diabase is much freer from zoning than that of any of the other types, and slightly more basic, having composition of about $Ab_{30}An_{70}$. Rims and interstitial areas of alkaline feldspar are entirely absent. The monoclinic pyroxene is characterized by its brownish-red color, slight pleochroism, strong inclined dispersion, and absence of twinning. The optic axial angle is generally about 45° and may be less in some cases. Judging by the optical and spectrographic evidence, the mineral appears to be a member of the magnesium-diopside series, the molecular percentages present being approximately: $CaSiO_3$, 40 per cent; $FeSiO_3$, 40 per cent; and $MgSiO_3$, 20 per cent. Biotite is present in small amounts as small but massive grains or rims in feldspar at black iron ore contacts. It is strongly pleochroic, being rich yellowish-brown with strong absorption parallel to the cleavage and pale yellow with little absorption perpendicular to it.

Alteration is very slight in this type of diabase. It is chiefly serpentinous material with black iron ore and some chloritic substance in feldspar associated with olivine. Some saussuritic material has developed in the feldspar.

Owing to the small amount of pyroxene and automorphic character of the olivine, the lath form of the feldspar has been masked by mutual interference of the crystals. However, where pyroxene has developed, it is markedly interstitial.

No chilled marginal material from a dike of this type was examined.

Table III gives the chemical analysis of Specimen 2–68, together with the norm and symbol according to the C.I.P.W. classification. The most striking feature of the analysis is its extremely high magnesia.

An examination of Washington's collection of analyses[3] yields several which resemble that of Specimen 2–68 more or less closely. Of these, the closest is an olivine gabbro.[4] Three others are basalts.[5] The results of microscopic study were available for only the first two basalts. Both contain large amounts of phenocrysts, 20–25 per cent in the second. This, coupled with the fact that Specimen 2–68 itself contains about 7 per cent of plagioclase phenocrysts, suggests that the analysis does not represent the composition of a simple magma, but rather, of one modified by concentration of early products of crystallization in the magma-chamber.

TYPE III DIABASE

Type III diabase is practically identical with Törnebohm's Åsby-diabase[6] if his augite is the same as the monoclinic pyroxene of these rocks.

The plagioclase is much more strongly zoned than in Type IV diabase, and its average composition seems to be acid labradorite. Small amounts of alkaline feldspar occur as rims about plagioclase laths and as fine-grained interstitial filling between them, especially in the low olivine members of the group. This material shows no twinning, and it was impossible to determine whether it is orthoclase or albite. However, sharp transitions between the refractive indices of the plagioclase laths and this interstitial material, together with a trace of pink color in contrast with the green shade of the plagioclase laths, suggests that it is orthoclase. Interstitial primary quartz is seldom found in diabases of this type except in those containing little olivine. Like the alkaline feldspar, with which it is nearly always associated, it fills interstices between other primary minerals, principally plagioclase laths. It generally forms a mosaic of small, irregular, interlocking grains. It may be intergrown with alkaline feldspar to form granophyric textures. The other primary minerals are as in Type IV diabase.

[3] H. S. Washington, "Chemical Analyses of Igneous Rocks," *U.S. Geol. Surv. Prof. Paper 99* (1917).

[4] *Ibid.*, *No. 142*, p. 658.

[5] *Ibid.*, *No. 101*, p. 652; *Nos. 191, 192*, p. 664.

[6] *Op. cit.*, pp. 268–69.

Alteration is a good deal more extensive, and the alteration products are more varied, than in Type IV diabase. Serpentinous and chloritic material are best developed. Some of the latter is readily recognizable as penninite, with which granular epidote may be associated. Secondary alkaline feldspar, probably albite, is occasionally found filling veins. Paramorphic alteration of pyroxene to green hornblende occurs, but is rare. As a rule, the pyroxene is remarkably fresh, even when the other primary minerals are extensively altered. Small massive crystals of sphene may occur, especially with secondary alkaline feldspar and chlorite.

As the grain size decreases toward the margins of dikes of this class, olivine fails to develop. The pyroxene becomes more deeply colored and forms groups of slightly divergent blades. These are elongated parallel to crystallographic *c* and are far more automorphic than the markedly intersertal pyroxene in the central portions of the dikes. They are stippled with fine-grained, black iron ore; and small rods of this mineral are scattered through the thin-section, often gathered together to form small skeletal cubes. The actual contacts of the dikes are composed of brown microcryptocrystalline material showing banding parallel to the walls, and clouded by opaque material which may be fine-grained, black iron ore. The only easily identifiable minerals at the contact are plagioclase, which occurs as large phenocrysts and small, rounded laths, and small grains of yellow sulfide surrounded by narrow, relatively transparent halos.

TYPE II DIABASE

Type II diabase resembles Törnebohm's Kinne-diabase[7] closely except that olivine may have been entirely absent from the unaltered rock. It is a transition phase between the olivine diabases of Type III and the olivine-free diabases of Type I, combining a number of the petrographic characteristics of each.

The plagioclase resembles that of Type III diabase, but its average composition may be a trifle less basic. The pyroxene shows a mixture of the characteristics of that in the olivine diabases and that of the olivine-free diabases. It is probably intermediate between them in composition, resembling the latter rather more than the

[7] *Ibid.*, p. 265.

former. Twinning and poorly defined zoning are not uncommon. The birefringence and optic axial angle are more variable than in pyroxene of the olivine diabases. On the other hand, the color, though pale, tends toward pink rather than brown; and dispersion of the optic axes, though faint, is perceptible. If specimens are assigned to this group on the basis of the nature of the pyroxene, it is found that olivine may be entirely absent. On the other hand, small amounts of the mineral may be present in the usual well-rounded, automorphic grains.

The pyroxene is, as a rule, somewhat more automorphic than most of the pyroxene of the olivine diabases.

The alteration products are about the same as in Type III diabase. Serpentinous material is relatively rare, while chloritic material predominates. There is a good deal of massive hornblende developed paramorphically from pyroxene. Green hornblende predominates, though brown also occurs. Finally, a colorless mineral, which is probably talc, is occasionally found as rounded, felty masses more or less heavily speckled with black iron ore. These masses may well represent altered olivine grains, and in some sections are the only indication that olivine was originally present.

No marginal material from a dike of this type was examined.

TYPE I DIABASE

Type I diabase is practically identical with Törnebohm's Konga-diabase.[8]

The plagioclase is very similar to that of Type II, though its average composition may be as acid as basic andesine. The monoclinic pyroxene of this type of diabase is most readily distinguished from that of the other types by abundant twinning and very faint brown color. Zoning is generally marked. 2V is very variable and may approach 0 at the cores of grains. Dispersion of the optic axes is generally too weak to be noticeable in white light. Though Törnebohm calls the pyroxene of Konga-diabase "augite," Wahl concludes that it is magnesian diopside.[9] The optical properties of the pyroxene of

[8] *Ibid.*, pp. 260–62.

[9] W. Wahl, "Die Enstatitaugite," *Min. pet. Mitt.*, N.S., Vol. XXVI (1907), pp. 33–35.

Type I diabase and their variations are in excellent agreement with those given by him. No difference could be detected between the spectrograms of this pyroxene and those of the other types of diabase. Rich brown biotite at contacts between black iron ore grains and plagioclase is much rarer than in the other types of pyroxene. Interstitial primary quartz and alkaline feldspar are always present, often becoming quite abundant.

They not uncommonly form granophyric intergrowths. The outlines of the pyroxene areas are largely controlled by the plagioclase laths, though the inner zones of grains may be quite automorphic.

Alteration products are very much the same as in the other types of diabase, though rather more abundantly developed as a rule. Felty green material is common in feldspar and pyroxene. Some of it is probably chlorite and some amphibole. Serpentine could not be distinguished from the other green alteration products with certainty. Paramorphic alteration of pyroxene to green and brown hornblende is common. In some of the dikes, especially in the Okak section, the amphibole alteration products predominate strongly, and here leucoxene may be developed from black iron ore. Veins of secondary alkaline feldspar, probably albite, with associated pyrite and minute sphene crystals were occasionally noted.

Though the margins of dikes of this type show finer grain than the central portions, none were found to be microcryptocrystalline. No other difference in texture and no difference in mineral composition was noted.

COURSE OF CRYSTALLIZATION

The course of crystallization in this series of rocks is that of normal diabases. The large size and unzoned cores of the plagioclase phenocrysts indicates their intratelluric origin. All other minerals probably developed in the dike fissures.

Pyroxene appears to have formed progressively earlier from Type IV diabase to Type I diabase, and this is especially true of the high-magnesian cores of pyroxenes in Type I diabase.

A notable exception to the normal crystallization series is shown by the margins of Type III diabase, where olivine has failed to develop. Here pyroxene and black iron ore formed very early.

MOVEMENT IN THE SOLIDIFYING MAGMA

Flow banding in the microcryptocrystalline material at the contacts of Type III diabases indicates that the magma was still in motion when it first began to crystallize in the dike fissures. There are indications that this movement had not entirely ceased, even at the final stages of consolidation. These include polysomatic texture in pyroxene, abnormal biaxial character of some primary quartz grains, occasional bent or even broken plagioclase laths, and undulatory extinction in a few feldspars attributed to strain rather than zoning because of its irregularity. These evidences of strain are too sporadic in occurrence to indicate that the diabases as a whole have been subjected to any significant stress subsequent to consolidation. The relative scarcity of polysomatic texture in pyroxene of Type I diabase would be accounted for by its earlier crystallization.

AUTOMETAMORPHISM AND WEATHERING

It seems probable that much of the alteration of the diabases is the result of autometamorphism. Indications that regional or contact metamorphism have occurred are lacking. Yet such phenomena as veins of secondary alkaline feldspar, development of fine-grained, flaky scapolite in feldspar, and paramorphic alteration of pyroxene to massive hornblende cannot readily be attributed to weathering. Constant association of massive, dark brown biotite with contacts between black iron ore and plagioclase suggests that it is a synantectic alteration product developed soon after consolidation. The presence of sphene crystals, pyrite, green amphibole needles, and chlorite in alkaline feldspar veins shows that they have the same origin, at least in part.

A portion of the chlorite, as well as serpentine and black iron ore developed from olivine, may well be the result of weathering. Some of the other alteration products perhaps have the same origin. However, no criteria could be found by which weathering products could be distinguished with certainty from the products of autometamorphism.

DISTRIBUTION

Judging by the material studied, Type I diabases are most abundant in the northern part of the area, while the proportion of Type

III diabases increases toward the south until they are prevalent in the Hopedale region.

MAGMATIC DIFFERENTIATION

In view of the complete gradation in mineral composition throughout the series and the lack of geographical boundaries between the types, it seems probable that they have originated from a single magma by differentiation.

A rock such as Specimen 2–68 (No. 1, Table I) might be derived from a magma whose composition is similar to that of an intermediate member of the series by gravitative concentration of olivine and basic plagioclase, both early crystallization products, in the lower portions of the magma chamber. The presence of plagioclase phenocrysts of intratelluric origin in this rock, and the occurrence of phenocrysts in several of the rocks which most closely resemble it in Washington's collection of analyses,[10] favors this view. If such a process has occurred, large-scale re-fusion must have taken place, since the percentage and character of the phenocrysts in Specimen 2–68 are not what they should be if the rock had been derived in the manner suggested but without re-fusion.

Further evidence that differentiation by partial crystallization has occurred is given by the diabase represented in column 8 of Table I. In this dike there is a large, but variable, percentage of plagioclase phenocrysts in a groundmass which has the composition of typical Type I diabase. This suggests that it was derived from a magma with a uniform composition resembling that of Type I diabase simply by local concentration of labradorite phenocrysts in the magma chamber.

Such a process of differentiation by partial crystallization with gravitative concentration, and re-fusion, at least in the most basic members of the series, is in line with Vogt's theory.[11]

[10] *Op. cit.*

[11] J. H. L. Vogt, "The Physical Chemistry of the Magmatic Differentiation of Igneous Rocks, Part I," *Kristia* (1924).

AMERICAN DOCTORATES IN GEOLOGY

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For several years information concerning Doctor's degrees in the sciences granted currently by universities in the United States has been compiled by the National Research Council.[2] Statistics on doctorates in science for a number of the earlier years were published in *Science* and in *School and Society*.[3] As compiled in tabular form, these data have commonly shown the number of Doctor's degrees in geology granted in the United States in a given year and the number of degrees in all the sciences in each of the universities, but the data were not tabulated for the separate sciences by years for each university.

Using the titles of theses given in these earlier compilations, the writer has tabulated the figures for geology[4] for the more recent period by universities and years and has completed the earlier statistical history by correspondence directly with university departments or registrars and by the use of published circulars for individual universities.[5] The totals shown in the tables and diagrams are believed to be as nearly correct as it is practicable to obtain without an undue amount of further correspondence and searching. Persons acquainted with the early history of a given university may detect errors in the figures given for that university. The records in many universities are not so complete nor so accessible to present officials as might be desired. In some instances dates on titles of theses differ from those on which degrees were conferred, resulting in conflicting

[1] Doctor of Philosophy, Iowa, 1923.

[2] National Research Council, "Reprint and Circular Series," Nos. 12, 26, 42, 75, 80, 86, 91, and 95.

[3] *Science* (ann. vol., 1898–1915); *School and Society*, Vol. V, No. 110 (1917), pp. 145–49.

[4] Including mineralogy and paleontology.

[5] *Yale University Bull.* (24th ser.), No. 2 (1927); (27th ser.), No. 14 (1931); *Harvard University Register*, Vol. XXIII, No. 39 (1926); *Johns Hopkins University Circular*, N.S., No. 8 (1926); *University Chicago Announcements*, Vol. XXXI, No. 8 (1930).

statements. Classification of titles of theses and the difficulty of drawing a line between geology (including paleontology and mineralogy) and adjacent subjects such as geography, zoölogy, and botany has in some instances been a source of discrepancies between different statements from the same university. In spite of such sources of error, the data presented give a valid history of the doctorates in geology in America, the figures having been expanded to include Canadian universities as well as those in the United States.

Contributions to the early history of the Doctor's degree in the United States have been made by Bourne[6] and Perry.[7] Doctor's degrees granted abroad were first noted in an American college catalogue in 1821. One of the two Americans to be listed in the Harvard catalogue of that year as doctors of philosophy was Joseph Green Cogswell, who taught mineralogy and geology. Not until forty years later was the Doctor's degree granted in America, and then by Yale in 1867. Harvard first granted doctorates in 1873, two Ph.D.'s and one Sc.D. being awarded.

The first American doctorate in geology was awarded by Yale in 1867. Harvard, Cornell, and Columbia followed with first doctorates in geology in the years 1875, 1877, and 1879, respectively. By 1870 2 doctorates in geology had been granted in America, from 1871 to 1880 the number was 8, and in the decade from 1881 to 1890 16 more were added. Table I shows the history of the doctorate in geology by decades. Table II shows the names of the first seven men to receive doctorates in geology in America.

The increase in the number of universities granting the degree has been fairly uniform during recent decades. From 1 in 1870 the number reached 4 in 1880, 7 in 1890, and 15 in 1900. Since 1900 the increase in the three decades has been 7, 8, and 10, respectively, the total number in 1930 being 40. Prior to 1885 the average number of degrees per year per university among those which had granted the degree was 0.28; from 1886 to 1900 the rate was 0.47; from 1901 to 1915, 0.59; and from 1916 to 1930, 1.24.

[6] Edward G. Bourne, "Early History of the Degree of Doctor of Philosophy in the United States," *Educ. Rev.*, Vol. X (1895), pp. 81–84.

[7] E. D. Perry, "The Degree of Doctor of Philosophy in the United States," *ibid.*, Vol. XXVIII (1904), pp. 164–77.

The number of doctorates awarded per year in America has increased at a rate slightly in excess of a doubling of the numbers in each decade. If the 2 degrees between 1867 and 1870 be taken as a

TABLE I

AMERICAN DOCTORATES IN GEOLOGY BY DECADES

Decade	Universities Grouped According to Commencement of Degree-Granting	Total Number of Degrees
1867–70	Yale	2
1871–80	Harvard, Cornell, Columbia	8
1881–90	Princeton, Wisconsin, Johns Hopkins	16
1891–1900	Vanderbilt, Stanford, George Washington, Chicago, Ohio, California, Kansas, Toronto	69
1901–10	Nebraska, Virginia, Pennsylvania, Colorado, Washington and Lee, Massachusetts Institute of Technology, McGill	99
1911–20	Michigan, Bryn Mawr, Pittsburgh, Indiana, New York, Iowa, Illinois, Minnesota	180
1921–30	Missouri, North Carolina, Oregon, American, Washington (Seattle), Cincinnati, California Institute of Technology, Fordham, Radcliffe, Syracuse	390
Total		764

TABLE II

LIST OF THE FIRST SEVEN AMERICAN DOCTORS IN GEOLOGY

Name	University	Year
William North Rice (1845–1928)	Yale	1867
Edward Thomson Nelson (?–1897)*	Yale	1869
Henry Shaler Williams (1847–1918)	Yale	1871
Nathaniel Southgate Shaler (Sc.D.) (1841–1906)	Harvard	1875
Edward Salisbury Dana (1849——)	Yale	1876
Charles Whittlessey Foote*	Cornell	1877
Edward Raymond Benton*	Harvard	1878

*No dates of birth or death were given in official published lists of early graduates.

rate of 5 per decade and this rate had doubled each decade, the total to 1930 would be 632. The actual number to 1930 is 764. Though the degree was first granted in 1867, it was not until the quinquen-

nium following 1885, when seven universities had granted the degree at least once, that the rate of 1 degree per year had been established.

TABLE III

NUMBERS OF DOCTORATES BY YEARS AND QUINQUENNIA

Year	No.	Quinquennium Total	Year	No.	Quinquennium Total
1867	1		1901	11	
1868	0		1902	6	
1869	1		1903	15	
1870	0	2	1904	9	
			1905	7	48
1871	1		1906	14	
1872	0		1907	6	
1873	0		1908	6	
1874	0		1909	13	
1875	1	2	1910	12	51
1876	0		1911	14	
1877	1		1912	24	
1878	1		1913	19	
1879	3		1914	16	
1880	1	6	1915	28	101
1881	0		1916	23	
1882	0		1917	25	
1883	2		1918	10	
1884	0		1919	6	
1885	1	3	1920	15	79
1886	2		1921	13	
1887	1		1922	24	
1888	4		1923	36	
1889	4		1924	42	
1890	2	13	1925	29	144
1891	1		1926	39	
1892	4		1927	44	
1893	4		1928	41	
1894	7		1929	48	
1895	7	23	1930	74	246
1896	10		Total		764
1897	10				
1898	6				
1899	12				
1900	8	46			

By 1890 the rate was in excess of 2 per year and by 1895 it had reached 4. Between 1901 and 1910 a nearly uniform rate of 10 de-

grees per year was maintained and this rate was doubled in the five years that followed. The decrease in numbers of doctorates granted in 1918, 1919, and 1920 as a result of the World War resulted in a drop to 14 per year during the quinquennium 1916–20. Since

TABLE IV

TOTAL NUMBERS OF DOCTORATES IN GEOLOGY AND NUMBERS FROM 1921 TO 1930

University	No. of Degrees Granted		University	No. of Degrees Granted	
	All Time	1921–30		All Time	1921–30
Chicago	104	50	McGill	5	4
Yale	91	22	Indiana	4	3
Johns Hopkins	88	30	Virginia	4	1
Harvard	66	28	California Institute of Technology	3	3
Columbia	57	23	Ohio	3	2
Wisconsin	43	24	Vanderbilt	3	0
California	43	20	New York	3	2
Princeton	40	29	American	2	2
Cornell	33	19	Washington (Seattle)	2	2
Stanford	30	23	Missouri	2	2
Minnesota	22	21	Pittsburgh	2	1
Iowa	20	19	North Carolina	2	2
Michigan	17	14	Fordham	1	1
George Washington	17	10	Radcliffe	1	1
Massachusetts Institute of Technology	16	11	Syracuse	1	1
Toronto	13	9	Cincinnati	1	1
Pennsylvania	6	3	Oregon	1	1
Bryn Mawr	5	3	Colorado	1	0
Illinois	5	2	Kansas	1	0
Nebraska	5	1	Washington and Lee	1	0

1920 the rate has increased to a rate well over 50 doctorates per year (Table III).

The rank of universities in total numbers of doctorates in geology since their first award of the degree is shown in Table IV.

During the period from 1926 to 1930 the first 10 universities of the 40 in the list granted 69 per cent of the total number of degrees granted in that period. Nine of those listed granted no doctorates in geology during that period and several of these have been inactive for a considerably longer period. Somewhat similar concentration is

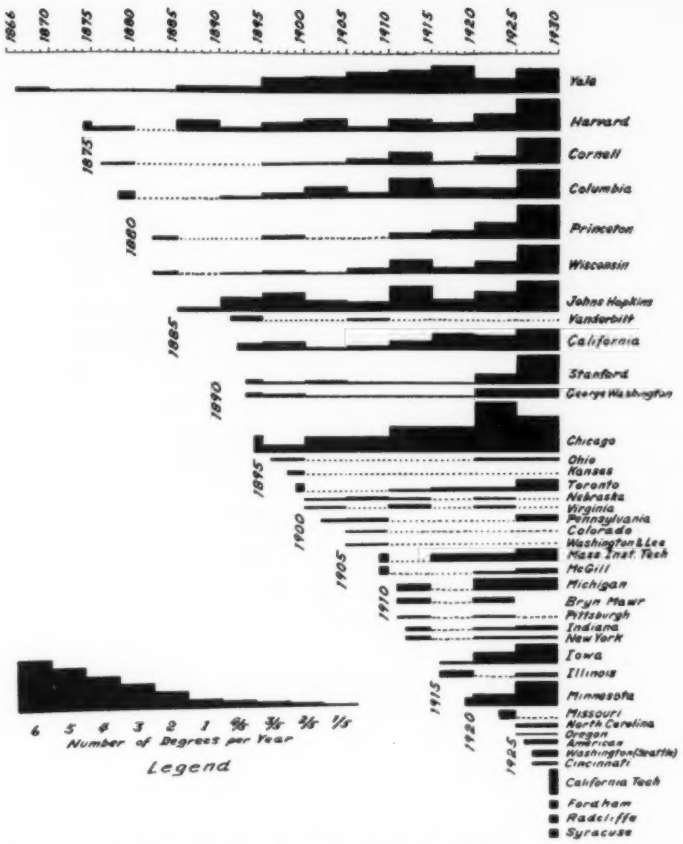

FIG. 1.—Bar diagram showing doctorates granted in geology (including mineralogy and paleontology) by American universities to the year 1930, inclusive. The left end of the bar in each case shows the year in which the degree was first granted in geology by a given university. The data for each five-year period, or initial fraction thereof, have been averaged to eliminate the extreme irregularity of the year-by-year data, and the width of each segment of a bar indicates the average number of degrees per year throughout a given quinquennium. The total may be obtained by multiplying by 5, or by a smaller number in initial periods. Thus it is apparent that the black area for each university and that in the whole diagram is strictly proportional to the number of degrees and constitutes a mass diagram for the period from 1867 to 1930, inclusive. It is unavoidable in such a diagram that the shape of the area for one degree should differ according to whether that degree is given early or late in the quinquennium. In spite of this shape irregularity, it was thought best to show the initial year accurately and to show continuous averages by five-year periods. Quinquennia during which no degree was given are shown by a dotted line.

naturally present in the all-time totals. Five universities, one-eighth of the total number, have granted 54 per cent of all the geology doctorates in America. Sixteen universities, or two-fifths of the total, have granted 92 per cent of the total. Among the 30 universities which have been granting the doctorate in geology for more than ten years, 2 have averaged 2 or more degrees per year for their entire period of nominal activity and 5 more have averaged more than 1 degree per year.

It is not the purpose of this paper to discuss the wisdom or desirability of the great expansion in members of doctorates which is in progress. The figures have been presented and arranged impartially to indicate the history and the current trend. With the great increase shown, it can scarcely be doubted that the doctorate is less a mark of distinction than it was a generation, or even a decade, ago. This decrease in relative value may be due in part to the diversity in standards which comes with multiplication of institutions granting the degree, but is perhaps mainly due to the great increase in doctorates granted in proportion to the population.

REVIEWS

Textbook of Geology. By CHESTER R. LONGWELL, ADOLPH KNOPF, and RICHARD F. FLINT. Part I, *Physical Geology*. New York: John Wiley & Sons, 1932. Pp. 514; figs. 341. $3.75.

One who reads this excellently written textbook is convinced that the authors must have been actively engaged in teaching general geology for a long time, and know from a full experience the many questions that arise in the minds of beginning students. The clear and pleasing style, the close correlation among the different topics presented, and the wealth of very pertinent illustrations combine to make this a book that is certain to be very popular among teachers of elementary geology. The general treatment of the revised Pirsson of 1929 has been retained, but many important changes and additions have been made, and several chapters have been completely re-written.

One of the noteworthy advances in this book is the dropping of the chapter on the work of the atmosphere and substituting for it chapter ii, "Rock Weathering," and chapter vii, "Erosion and Deposition by the Wind." In chapter ii is presented a unified treatment of all of the various agencies of weathering. Several years ago Foye emphasized in *Science* the necessity of this, pointing out, for example, that "it is poor physics to teach that exfoliation due to changes of temperature alone is the work of the atmosphere." In the following chapters on "Running Water," "Subsurface Water," and "Glaciers," paragraphs on weathering as an accompanying process give a unifying coherence to the discussion of the various degradational agencies.

In chapter iii, "Running Water," the analysis of the factors of fluvial erosion is more definitely expressed than in the older book. An excellent, well-illustrated treatment of the fluvial cycle of erosion of a land area or region under different climatic conditions is given, but the very useful conception of youth, maturity, and old age in a single valley is omitted, except as implied in the diagram and photograph on page 47.

In the chapter on glaciers one notes with relief the elimination of much detail that is superfluous in an elementary course, such as the various hypotheses on the mechanism of ice flow. On the other hand, more discussion of the causes of glaciation might have been given. Such a discus-

sion is given in Part II, but students almost invariably ask for an explanation at this point.

The treatment of the topics of "Erosion and Deposition by the Wind," "Marine Erosion and Deposition," "Sedimentary Rocks," "Igneous Rocks," and "Vulcanism" follows the same high standard set by the revised Pirsson, some new material has been added, and the whole is more teachable. The addition of diagrams to illustrate the elastic rebound theory for earthquakes remedies a fault of the revised Pirsson. New paragraphs on predicting earthquakes and precautions against earthquakes will provoke interesting discussions among students. In the chapter on metamorphism is given a good, illustrated description of the origin of mylonites and a more lucid treatment than we have had before of the classification and relationships of the finer-grained foliates in the series slate-phyllite-schist. The entire chapter definitely emphasizes that metamorphism of rocks is the direct result of adjustment to environment, to changing stability conditions.

Chapter xviii is entitled, "Mineral Resources," and is intended to be broader in scope than the chapter on "Ore Deposits" in the 1921 Pirsson. It gives an excellent elementary discussion of coal, its nature, origin, occurrence, chemical composition, classification by rank, and the relation of rank to its geologic history. The evolution of coal to higher ranks is ascribed entirely to intensity of metamorphism. No mention is made of the possibility of change to at least bituminous rank by reason of permeability of overlying rocks, through either porosity or fracturing, permitting the escape of volatile matter and raising the percentage of fixed carbon. Likewise, a clear and logical presentation of petroleum and gas is given—conditions necessary for occurrence, life of oil wells, functions of gas in oil field operations, and some of the remarkable results obtained by geophysical prospecting, especially in connection with salt domes. Under the first topic the author apparently believes in plant remains exclusively as the source of oil. With this hypothesis many petroleum geologists will not agree. The inclusion of the mineral fuels in this chapter is a very happy addition to the text and fills a decided need.

It appears to the reviewer, however, that the exposition of "Ore Deposits" is not so successful as the rest of the book, and he would have preferred the retention of the Bateman discussion, simplified somewhat for the elementary student. As the majority of students will go no farther in the subject of economic geology than the beginning course, a more nearly complete presentation should be given them. There is nothing on the physical conditions of temperature and pressure under which primary

ore deposits are formed, and very little on the nature of ore solutions. The discussion of replacement is inadequate. The principal ore and gangue minerals are not listed, as they were in the Pirsson, and only a few of them are included in Appendix A. The chapter also has a lack of balance. There is a remarkably fine discussion of iron ores, which is used to illustrate principles of certain processes of deposition, but one wonders why so much space is given to iron, to the exclusion of copper, lead, zinc, and other metals. A somewhat lengthy and very illuminating exposition of placers is given, but nothing on secondary enrichment.

One of the principal criticisms of the Pirsson textbook and its revisions, on the part of teachers of geology, has been the order of arrangement. Descriptions of minerals and rocks are placed in appendixes rather than early in the text, and the chapters on origin and occurrence of igneous, sedimentary, and metamorphic rocks come in the middle and latter part of the book. The same arrangement is used in this book. Most teachers feel that a beginning course in geology should start with materials of the earth. That the authors of this book are in accord with this view is shown by their remarks in the Preface, but they feel that much is gained by segregating the purely descriptive matter in the appendixes, to be used in the laboratory. It is difficult for the student to grasp the fundamentals of origin and occurrence of rocks until he has had some training in other geologic processes, especially the principles of sedimentation, vulcanism, and metamorphism. Thus the chapters on the rocks logically follow the chapters on those principles. (It is suggested that the chapter on igneous rocks should follow, instead of precede, that on vulcanism, as in the Pirsson text.) After a very considerable experience in teaching elementary courses, the reviewer has been gradually converted to this order of arrangement, and feels that if the suggestions of the authors are followed it is a very successful one.

The book is remarkable for its fine illustrations. A great many well-executed block diagrams are used, giving the student a clearer conception than he can gain from two-dimensional diagrams. Most of the halftone illustrations are new and are well chosen. More use of aerial photographs might be made, as many excellent ones are in existence. Medium to low oblique pictures should be used, as vertical or high oblique photographs are not very successful for most illustrative purposes.

The mechanical features of the book are almost perfect. It is attractively bound in maroon buckram. Only one or two printers' errors were noted. The paper is not highly surfaced as in predecessors of this text. Objectionable glare is thus avoided, but at the same time the press work

on the halftones is so excellent that no detail is lost. In spite of a greater number of pages there is no increase in the weight of the book. The price is the same as the 1929 revised Pirsson.

JOSEPH P. CONNOLLY

Über das Alter der Schieferung und ihr Verhältnis zur Faltung. By HERMANN SCHOLTZ. *Jahrbuch der Preussischen Geologischen Landesanstalt*, Vol. LII (1931). Pp. 303–316.

Das varistische Bewegungsbild. By HERMANN SCHOLTZ. *Fortschritte der Geologie und Palaeontologie*, Vol. VIII, No. 25. (1930) Pp. 235–312.

Recently Dr. Hermann Scholtz, of the Bonn Geological Institute, has published two papers of unusual interest to structural geologists, in which he has completely abandoned the theories of Becke, Grubenmann, and Born relating to the origin of crystalline schists and to the origin and significance of cleavage.

The general principles of Becke, Grubenmann, and Born, very briefly stated, postulate that crystalline schists are developed through a sort of static crystallization. Becke, for instance, states that schists are characterized by those minerals whose molecular volumes are less than the volumes of their constituent oxides, as contrasted to the igneous rocks, the minerals of which have molecular volumes greater than the volumes of their constituent oxides. With this premise, he argues that the former are controlled and developed by pressure and the latter by heat, which acts against and withstands pressure. Grubenmann relates the origin of different types of schists to three different zones of depth: the first, a zone of moderate temperature, low hydrostatic pressure, and exothermic heat reactions; the second, a zone of higher temperature, intense differential stresses, stronger hydrostatic pressure, and both exo- and endothermic heat reactions; and the third, a zone of enormous temperature and hydrostatic pressure, very feeble differential stresses, and endothermic heat reactions. Differential stress is recognized as a factor in the development of schists, but only as a supplement to several other controlling factors. He cites certain mineral changes which are typical. For example, olivine of the lowest zone becomes hornblende or garnet in the middle, and serpentine in the upper zone.

These views have represented, in general, the German concept of the important factors which control the development of schists. An alterna-

tive hypothesis, first presented in 1896 by Van Hise, and subsequently developed by Leith (C. R. Van Hise, "Principles of North American Pre-Cambrian Geology," *16th Ann. Rept., U.S.G.S.* (1896); C. K. Leith, "Rock Cleavage," *Bull. 239, U.S.G.S.* (1905) and *Structural Geology*, New York, [1913]), places the control in differential movement and in differences in the competency and original composition of the subject rocks, assigning minor rôles to depth, temperature, and static load.

Dr. Scholtz has essentially adopted this hypothesis as a result of his detailed studies in the Hunsruck *Schiefer* and the Nuttlarer *Dachschiefer*. He has proved by a great number of observations that cleavage and compressional folding are results of the same deformation process, that the two have definite interdependence, and that the development of cleavage is proportional both to the amount of folding movement and to the relative incompetency of the folded beds. As far as his observations have gone, he distinctly emphasizes that depth of burial has not been a dominating influence. His illustrations, which are excellent, show unusually good examples of fracture cleavage cutting earlier flow cleavage and sometimes bending the flow cleavage into minor crenulations.

A few of his interpretations of cleavage do not apply in other areas. For example, in the Hunsruck schists his illustrations show that fracture cleavage (which he names *Schubkluftung*) has developed subsequent to flow cleavage and has displaced and wrinkled it. From this he has drawn the conclusion that fracture cleavage always develops subsequent to flow cleavage. His reason, and it seems to be valid in the area which he has studied, is that folding and its accompanying development of flow cleavage may progress up to a certain limit determined by the plasticity of the rocks and the confining pressures. Beyond this limit the rocks fail by fracture cleavage in a more steeply inclined direction than that of the axial plane. By collecting many observations of the two types of cleavage over a large area, he is able to show that some apparent variations from parallelism in the axial planes of different folds in the same general deformation (fan-structure) are due to this gradual turning away of the cleavage because of a change in type of rock failure and a change in the direction of relief. Under certain conditions, continued movement subsequent to the development of the fracture cleavage may rotate that cleavage until it is parallel or nearly parallel to the flow cleavage.

Scholtz's conclusion that fracture cleavage forms in the manner described and always later than flow cleavage is not tenable when we consider the almost innumerable cases which show that fracture cleavage may develop entirely independently, and that either type of cleavage may de-

velop to the exclusion of the other. This may be due to competency relationships in the deformed rocks, or it may be due to the type and amount of differential movement: at any rate, it is quite certain that no infallible controlling time-relation governing their sequence of development can be postulated and maintained. In many places the reverse of Scholtz's conclusion holds, i.e., the fracture cleavage is formed first and may be partially or wholly eradicated by later flow cleavage. The statement that fracture cleavage can be rotated until it lies approximately in the plane of the flow cleavage opens to some extent the question of definition. Undoubtedly fracture cleavage can be rotated by a continuation of the folding and shearing movement which produced it, but such continued shearing is usually accompanied by mineral changes so that the fracture cleavage becomes flow cleavage.

Dr. Scholtz has not yet attempted to analyze mechanically his multitude of observed relations between cleavage and bedding planes, and has not reduced these relationships to a strain ellipsoid from which the approximate position of the planes of maximum shear can be related to the directions of elongation and shortening.

ANDREW LEITH

Origin and Environment of Source Sediments of Petroleum. By PARKER D. TRASK, assisted by HARALD E. HAMMAR and C. C. WU. Houston, Texas: Gulf Publishing Co., 1932. Pp. xv+323; text figs. 38; one folding plate. $6.00.

This book records the results of five years' work by Dr. Trask and his associates upon Recent sediments of types which might yield petroleum in a future geological period. The enterprise was financed by John D. Rockefeller through the American Petroleum Institute. It was the first portion of a twofold task, the second part of which will be the investigation of the possible source sediments for some of the existing accumulations of oil.

Dr. Trask found it necessary to make a wide survey of the texture, carbonate content, and organic matter of marine sediments, especially those accumulating near shore. Two thousand samples were studied, of which one thousand were collected by Trask himself. These samples are considered to represent 150 local environments, a few lacustrine, and the remainder distributed through most, but not all, parts of the oceans. It will be seen that, though the object was geological, the work was almost exclusively oceanographic.

Because time and personnel were limited, it was only possible to com-

plete the project by supplementing the detailed quantitative studies (by Hammar and Wu) with more rapid quantitative, or at least semi-quantitive, work. For example, nitrogen determinations were found to be satisfactory for the estimation of organic matter. Mechanical analyses were made by a newly developed cumulative sedimentation method, using a centrifuge. Carbon dioxide was estimated from the comparative effervescences or by other rapid methods. The probable errors of most of the methods were more or less exactly determined. The author's frankness and the obvious necessities of the case disarm criticism, but it seems unfortunate that much of the work must ultimately be done again.

Some of the conclusions reached are of exceptional interest. Deltaic deposits contain little organic matter; deep sea deposits almost none. The loci of rich organic matter in the sea are near shore in local basins, especially in the vicinity of upwelling deep ocean water. That is to say, organic matter is abundant where settling basins underlie areas of surface water favorable to the development of phytoplankton. Apparently, liquid hydrocarbons are not part of the organic matter present in sediments at the time of their deposition; at least no such hydrocarbons were found in the analyses made during the course of this investigation. The calcium-carbonate content of sediments is rather closely proportional to the salinity of the surface water. Coarser sediments occur on ridges and steep slopes and finer sediments in relatively flat places, almost irrespective of the depth of water. This indicates that, even at depths of thousands of feet, the bottom may be swept by currents, perhaps of tidal nature.

There are also incidental applications of the general results. The conjecture is hazarded that the Paleozoic seas may have been as salty as the present oceans. In another connection it is suggested that, if coarser sediments occur on salt domes than in the surrounding correlative beds, it is probable that the domes were relatively ancient features of the sea floor. Again, an attempt is made to show that the silica of the Monterey (California Miocene) diatoms may have come from deep upwelling as well as from volcanic ash, and that the limiting factors for the development of these diatoms were probably phosphorus and nitrogen rather than silica.

The book seems to the reviewer to be one of the outstanding contributions to those phases of oceanography which are of geological interest. It may well become one of the indispensable reference works of the sedimentary petrologist.

A. O. WOODFORD

Summary Information on the State Geological Surveys and the United States Geological Survey. By M. M. LEIGHTON. Bulletin National Research Council, No. 88. Washington, 1932. Pp. 136. $1.00.

This report has been prepared to meet a wide need for information on the present geological surveys of the country. Each state is treated in alphabetical order under the following headings: "Scope of Activities," "Organization," "Appropriations," "Publications," "Principal Accomplishments since 1911," "Present Main Lines of Work," and "Previous Survey Organization." Much useful information is thus made available. Perhaps the most striking item of general interest is the great variation in the appropriations of the states for geological work. Some states provide many times the average state appropriation, and comparisons of the accomplishments of the different surveys should take into account the funds with which they have to work.

Dr. W. H. Emmons wishes to make the following correction:

On page 59 of Bulletin 88 of the National Research Council there is a review of the geological work done in Minnesota by the State Geological Survey. A certain statement implies that there was little geologic work done in Minnesota between 1872 and 1900; this should read "between 1900 and 1912." As most geologists in America will recall, there was an active State Geological Survey of Minnesota between 1872 and 1900 under the able direction of Dr. N. H. Winchell. This Survey issued a fine series of reports including 24 annual reports, 10 bulletins and a magnificent 6-volume series with colored county maps on the geology, paleontology, and mineral resources of the state, entitled the *Final Report of the Survey.*

R. T. C.

Symposium on Salt Domes. Containing papers by JAMES ROMANES, G. M. LEES, F. G. CLAPP, J. V. HARRISON, ARTHUR WADE, E. DE GOLYER, LAUNCELOT OWEN, MURRAY STUART, HAROLD DABELL, KARL SUNDBERG, and CARL SCHMIDT. London: Institution of Petroleum Technologists. Pp. 132; figs. 12; pls. 3; maps 8. 10*s.* 6*d.*

This collection of papers deals with the salt domes of Germany, Egypt, the coast of the Gulf of Mexico, Asia Minor, and particularly Persia. There are included articles on the physics and chemistry of these structures. Noteworthy is a lively discussion concerned primarily with the origin of the Persian domes, resulting from the contributions of Lees and Harrison. This collection of selected articles should be in the library of every geologist working in salt-dome areas, for they constitute a valuable contribution to the literature of this subject.

H. W. STRALEY III

PUBLICATIONS RECEIVED

Minerals of Connecticut. By John F. Schairer. State of Connecticut, State Geological and Natural History Survey Bulletin No. 51. Hartford: Published by the State, 1931.

The Red River Lobe of the Moreno Glacier. By Robert W. Ellis. University of New Mexico Bulletin. Albuquerque, New Mexico: University of New Mexico Press, 1931.

Revue des questions scientifiques. Société Scientifique de Bruxelles, Paris: 1932.

Tectonics of the Zone of Don-Medviditsa Uplifts. Attitude of the Carboniferous Beds in the Don Region. By S. Semichatov. Transactions of the Geological and Prospecting Service of U.S.S.R. Fascicle 62, 1931.

Records of the Geological Survey of India, Vol. XLV, Part I (1931). Calcutta. 1931.

Report on the Geology of the Region to the North and North-West of Tarcoola. By R. Lockhart Jack. Geological Survey of South Australia. Adelaide: Harrison Weir, 1931.

Report of the Scientific Results of the Norwegian Expedition to Novaya Zemlya, 1921. Edited by Olaf Holtedahl. Oslo: A. W. Broggers Boktrykkeri, 1930.

Some Salt Lakes of the Northern Rift Zone. By Douglas Orr and D. R. Grantham. Paper No. 8, Geological Survey Department, Tanganyika Territory. Dar Es Salaam: Government Printer, 1931.

Source Material for the Social and Ceremonial Life of the Choctaw Indians. By John R. Swanton. Smithsonian Institution, Bureau of American Ethnology, Bulletin 103. Washington: U.S. Government Printing Office, 1931.

Spatglacialen Niveauverschiebungen in Finnland. By Wilhelm Ramsay. Helsingfors: Helsinki, 1931.

Summary of Progress of the Geological Survey of Great Britain and the Museum of Practical Geology for the Year 1930, Part I, II, III. London: His Majesty's Stationery Office, 1931.

Suomen Geologisen Seuran Julkaisuja Meddelanden från Geologiska Sällskapet i Finland. Comptes rendus de la Société géologique de Finlande. Bulletin de Commission géologique de Finlande, No. 93. Helsingfors: Helsinki, 1931.

Tertiary Foraminifera from Humboldt County, California. By Joseph A. Cushman and R. E. and K. C. Stewart. Transactions of the San Diego Society of Natural History. San Diego, California, 1930.

Übersicht über die Geologie des Felsgrundes im Küstengebiete zwischen Helsingfors und Onas. By C. E. Wegmann. Petrologische Übersicht des Küstengebietes E von Helsingfors. By E. H. Kranck. Bulletin de Commission géologique de Finlande, No. 89. Helsingfors: Helsinki, 1931.

Upper Eocene Orbitoid Foramanifera from the Western Santa Ynez Range, California, and Their Stratigraphic Significance. By W. P. Woodring. Transactions of the San Diego Society of Natural History. San Diego, California. 1930.

SIXTEENTH SESSION OF THE INTERNATIONAL GEOLOGICAL CONGRESS

The third circular for the Sixteenth Session of the International Geological Congress, which is to meet in Washington, U.S.A., from July 22 to 29, has been issued. It contains full information about meetings and about excursions, with costs. Before the Congress there are excursions to various parts of the Eastern United States, lasting from four to twelve days, and a transcontinental excursion eastward from San Francisco for those coming to the Congress from the West. For those arriving at New York too late to take part in these longer excursions there will be a number of short trips to nearby areas of geologic interest. Alternate days during the sessions will be given to excursions to areas around Washington.

After the sessions there will be two longer transcontinental excursions, each lasting thirty-one days, and two shorter excursions, one for the study of the glacial geology of the Central States, the other for the study of the pre-Cambrian area, including the iron and copper deposits, of the Lake Superior region. In order to make these excursions generally available, it has been possible, through the generous assistance of the Geological Society of America, to offer the longer excursions at a considerable reduction below actual cost.

For special discussion at the scientific sessions in Washington the following topics are announced:

Measurement of geologic time by any method.
Batholiths and related intrusives.
Zonal relations of metalliferous deposits.
Major divisions of the Paleozoic era.
Geomorphogenic processes in arid regions and their resulting forms and products.
Fossil man and contemporary faunas.
Orogenesis.
Geology of petroleum.
Copper resources of the world.

Membership in the Congress is open to anyone interested.

For a copy of the third circular or other information address W. C. Mendenhall, General Secretary, U.S. Geological Survey, Washington, D.C.